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A VISUAL ILLUSION OF MOTION DURING EYE CLOSURE

BY

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CONTENTS.

I. Introductory. Statement of Problem 1
II. Apparatus and Method 3
III. Lateral Displacements due to Closure 6
1. Cases having Zero Points 6
A. Location of the Zero Points 6
B. Direction of Movements in reference to Zero Points . . 15
C. Length of Movements in reference to Zero Points . . 23
2. Cases with no Zero Points 28
3. General Summary 30
IV. Lateral Movements due to Binocular Closure 30
V. Lateral Displacements due to Finger Pressure 33
VI. Lateral Displacements due to Suction 34
VII. Lateral Displacements during Normal Rotations 36
VIII. Sagittal Rotations of the Visual Field 37
IX. Unequal Displacements in Different Parts of the Visual Field 38
X. Changes in Size, Form, and Brightness of the Displaced Images 45
XI. Third Dimensional Movements 47
XII. Corresponding Eye Changes 52
1. Historical 52
2. Rotary-Displacement Movements of the Eye 58
3. Refractive Changes 73
XIII. Visual Phenomena due to Eye Movements 75
XIV. Visual Phenomena due to Refractive Changes 77
XV. A Statement of a Class of Visual Illusions of Motion in Terms of Muscular Innervation 79
XVI. Explanation of the Third Dimensional Movements . . . 111
XVII. The Space Significance of Ocular Innervation 117
Appendix. General Résumé 123

A Visual Illusion of Motion during Eye Closure.

I. Introductory.

Every one is more or less familiar with the doubling of objects due to external pressure upon the eyeball. The same phenomenon occurs with many people in every case of eye closure. This can easily be observed by winking slowly at a bright object, such as a street lamp, situated some distance away. The image of the non-winking eye remains stationary, while that of the winking eye gradually moves laterally in a definite direction until its vision is intercepted by the closing lid. On opening the eye, the movement is reversed in direction; the moving image is first seen at its place of disappearance, and gradually moves back toward the stationary image, the two again becoming combined.

The phenomenon is difficult to observe in ordinary cases of eye closure, because of the rapidity of the act, our habit of neglecting one of the double images, and the lack of vividness and disparateness of ordinary objects. By winking slowly at a very bright and sharply defined object, the phenomenon is easily detected and, with practice, it can be observed with all objects. The phenomenon occurs whether the other eye is open, closed, or has its vision intercepted in any way. By thus intercepting the vision of the non-winking eye, the movement at once becomes very noticeable, though there are no means of accurately estimating its direction and extent, because of the lack of any stationary image to serve as a point of reference. The movement refers not only to the object fixated, but to all objects in the visual field. The *whole* visual field of the winking eye is moved, or spatially displaced; the two visual fields are no longer superimposed, and all objects are doubled.

The phenomenon was first observed during involuntary blinkings, when the image of a window was reflected from behind by glasses. The reflected image was bright, sharply defined, and viewed monocularly, and hence its movement was very conspicuous.

After much blind and often futile experimentation, the following additional facts were discovered. For a definite position of the head, and a definite degree of convergence, there is one position, *a*, for each eye where winking produces no image movement, while there is movement for any other position, *b*, of the eye. Furthermore, the amount and direction of the movement for any position, *b*, are apparently related to the distance and direction respectively of *b* from *a*. To be specific, let the head assume a definite position at a certain distance from a vertical screen, so that the eyes by rotation can sweep over its entire extent and fixate any point without changing the position of the head. Taking the case of the right eye, there will be one and but one point, *a*, on the screen, which when fixated will not move upon winking. Suppose the point, *a*, to be near the center of the screen, and the eyes to rotate so as to fixate any other point, *b*, on the screen. Upon winking at this point, an image movement always occurs, and its direction apparently is always peripheral from *a*, — the place of no movement. If *b* is to the right of *a*, the movement is toward the right; if *b* is above *a*, the movement is upward; if *b* is located to the left of *a*, the field moves to the left, etc. The amount of the movement again seems to have reference to *a*, the greater the distance of *b* from *a*, the greater is the resulting movement.

The same description applies also to the left eye with the exception that *a*, the place of no movement, is differently located.

Many other interesting features were discovered and will be later described. The above facts are those necessary to understand the series of experiments which follow. It is obvious that we have to do with facts of spatial localization and the movement consciousness. The primary purpose of the experiments

is (1) to determine and define this position of no movement, *a*, (2) to discover by accurate measurements the relation of the amount and direction of the image movement for any position, *b*, to the distance and direction respectively of *b* from *a*, (3) to make comparative tests on a series of subjects, and (4) to determine, if possible, the conditioning physiological processes.

For the sake of convenience, the places of no movement will be called "zero points," and the image movements within the plane of the screen "lateral movements," to distinguish them from certain third dimensional movements later to be described.

II. Apparatus and Method.

A screen was constructed in one end of the room by tightly stretching a dull black cloth over a rigid rectangular frame.[1] Over this was stretched a system of parallel horizontal and vertical white cords, 5 cm. apart. Thus the whole screen was divided, checker-board fashion, into 5 cm. squares. The screen was firmly fastened in position, care being taken that its position was exactly vertical, the cords horizontal and vertical and the 5 cm. divisions practically exact. The observer was stationed in the other end of the room, 290 cm. distant. This distance was chosen at random, being the most convenient for the size of the room. Every part of the screen could easily be fixated without discomfort by mere eye rotation. The horizontal sweep of the eyes across the screen was 45°, and the vertical 35°.

For a head-rest, the common mouth-bit form was used, a

[1] A plane screen was used because of the difficulty of accurately constructing a spherical surface, and because of the greater ease in determining the direction of the image movements in reference to the zero point by triangulation. A spherical surface, on the other hand, would allow of a more accurate comparison of the length of the image movements in relation to the distance of the fixation position from the zero point; with a plane surface, the lengths of the movements are slightly increased for peripheral fixation positions because they are measured against a surface not perpendicular to the line of sight. A spherical surface would have permitted a comparison between angular, and not linear, values.

sealing wax mould on a piece of wood. This wood was bolted fast to an iron rod supported at either end by two firm iron uprights. These uprights were securely fastened to a heavy table, and this to the floor. The whole apparatus was extremely rigid and immobile. The cross bar was fastened to the two uprights by a system of clamps, so that the head could be raised or lowered, or adjusted in any of the three planes.

The object, the movement of one of whose images is to be measured, must be small, very bright and sharply defined. For this purpose an electric light was constructed, consisting of a single straight tube, 20 cm. long and 1 cm. in diameter, with a single straight filament running to its connections at either end of the tube. This light was fixed in a light wooden holder, which was screwed fast to one end of a small iron rod, around which the conducting wires were wound. This rod was fastened to a long upright stand by suitable adjustable clamps, so that the light could be adjusted in any position to any chosen spot on the screen. The stand, adjusting mechanism, wires, wooden frame, connections, and the two ends of the tube were painted a dull black. When this apparatus was placed against the black screen, a mere strip of intense light, 1×10 cm., was distinctly seen against the checkered background. Actually of course the whole visual field of the winking eye would move, all objects — strings, light, and mechanism — becoming double, but only the light was intense enough so that its movement could be seen. Consequently, upon winking at the light with the right eye, the left remaining open, the left eye's image of the background, strings and light would remain stationary and distinctly visible, while the winking right eye would see only an image of the strip of light moving off in some direction over the stationary system of white lines seen by the left eye. By this means the direction and extent of the lateral movements could easily be measured.

Having the observer's head fixed in the position desired, an assistant moves the light over the field so as to determine in a

general way the location of the zero point. He then places the light some distance above, and gradually moves it downward until the observer can detect no movement. The same process is repeated by moving the light from below, and from right and left. Several determinations are made, and repeated on successive days. Having the zero points located, various positions on the screen at regular intervals around the zero point are chosen. Knowing from preliminary experiments the general direction of movement at any place, the assistant adjusts the light so that its length will be perpendicular to the direction of movement. The light is so placed at one of the chosen positions that a sharply defined end is seen by the observer exactly at the point of intersection of the two white cords. The observer fixates this end and winks, noticing the direction and extent of the movement across the lines, and giving the assistant an accurate idea of the place of disappearance. The assistant then sticks a pin in the cloth at this point. The process is repeated until the observer is sure that the pinhead marks the place of disappearance. The distance between the pinhead and the intersection of the lines where the light was placed is measured by a millimeter rule, giving the extent of the movement. Knowing the positions of the zero point and the light on the screen, their distance apart may be computed, and the ratio of the amount of movement to this distance determined. The vertical and horizontal components of the movement along the white lines are measured, and from these results the direction of the movement in reference to the zero point can be determined by triangulation.

In the preliminary series of tests, various sources of error and fluctuation were noted. Both the direction and the extent of the movement vary with the character and the intensity of the winking act. Quite noticeable variations can be produced voluntarily in this manner. As the lids are nearly closed the image becomes fainter, merging into a positive after-image. Consequently the length will vary slightly, and it is difficult to

judge accurately just where the image disappears. All observers were given preliminary practice in observing the movements and making judgments. Attention was called to these sources of error, and the endeavor made to cultivate and maintain throughout the tests a steady and uniform method of winking and judging. As formerly mentioned, the observer was allowed as many trials as desired for each position, before judgment was made. The only guarantees of constancy of these varying conditions are the subjective feeling of uniformity, the tendency to habitual modes of response, and the number of trials allowed. Errors are undoubtedly present, but they have been minimized as much as possible.

Six subjects, (1) H. A. C., (2) J. R. A., (3) C. G. L., (4) C. J. W., (5) J. B. W., and (6) J. B. A., were used in the tests. All are trained and competent observers. The writer's case was studied with much care and detail, while lack of time and weakness of eyes in several subjects prevented any further detail than that necessary for comparative purposes. All six subjects exhibited these lateral displacements with closure, but only the first three possessed zero points, and the characteristic movements formerly outlined. Consequently these cases will be first considered, defining the location of the zero points and the length and direction of the movements in reference thereto. After this, the other three cases will be considered in detail, followed by a description of various other peculiarities connected with this phenomenon.

III. Lateral Displacements due to Closure.

1. *Cases having Zero Points.*

A. *Location of the Zero Points.* Since the zero points are really certain positions of the eyes in relation to the head, they must be defined in reference to some like and known constant relations. These are the primary position of the eyes and the median plane.

The primary position was determined by the usual negative after-image method. The position of the colored cross on the screen was so taken that, when fixated, the line of sight was perpendicular to the screen. The head was then adjusted around the horizontal and vertical axes until the primary position was secured, the line of sight still being perpendicular to the plane of the screen. The line joining the centers of rotation of the two eyes must be made horizontal, or level with the horizontal line of the screen cutting through the point of fixation. This is done by sighting over the sharp tip of a steel rod so placed that either eye will see it projected on the screen equidistant from the point of fixation of the primary position. If the right eye sees the projection of the tip just touching the horizontal string, while the left eye sees it projecting above, the left eye is too low, *i. e.* the eyes are not in the same horizontal plane. By adjustment of the head-rest, the head can be turned about its sagittal axis until the projection of the tip is seen by either eye just to touch the horizontal string. In this case, the eyes are level with the string, or are in the same horizontal plane.

In a few cases, it was found that while the eyes were thus level in reference to the line on the screen situated in the horizontal plane of the eyes, yet when tested for any other horizontal line, they were no longer "level," as it were. Thus, in fig. 1, *X* is the point of fixation of the primary position, and *A*, *B*, are two points on a horizontal line, 100 cm. distant from *X*. The right eye sees the tip of the rod projected at *A*, and the left eye at *B*. Looking up and sighting for the horizontal line 90 cm. above *AB*, the right eye sees the tip projected at *C*, while the left eye sees it at *D*, 7 cm. below the horizontal. Sighting for the line 90 cm. below *AB*, while the tip is seen projected at *E* by the right eye, the left eye sees it at *F*, 7 cm. above the horizontal. That is, the same length of rod subtending the distance *CE* for the right eye would subtend *DF* for the left eye. Yet *DF* is 14 cm. shorter than *CE*. Consequently, the left eye must be further away from the tip of the rod than the right eye. This

greater distance was computed to be 5+mm. in order to explain the discrepancy of 14 cm. Actual measurements of the distances of the tip from the corneas by two assistants gave an average result of 5 mm. While the line joining the centers of rotation of the two eyes is in the same horizontal plane as *AB*, yet

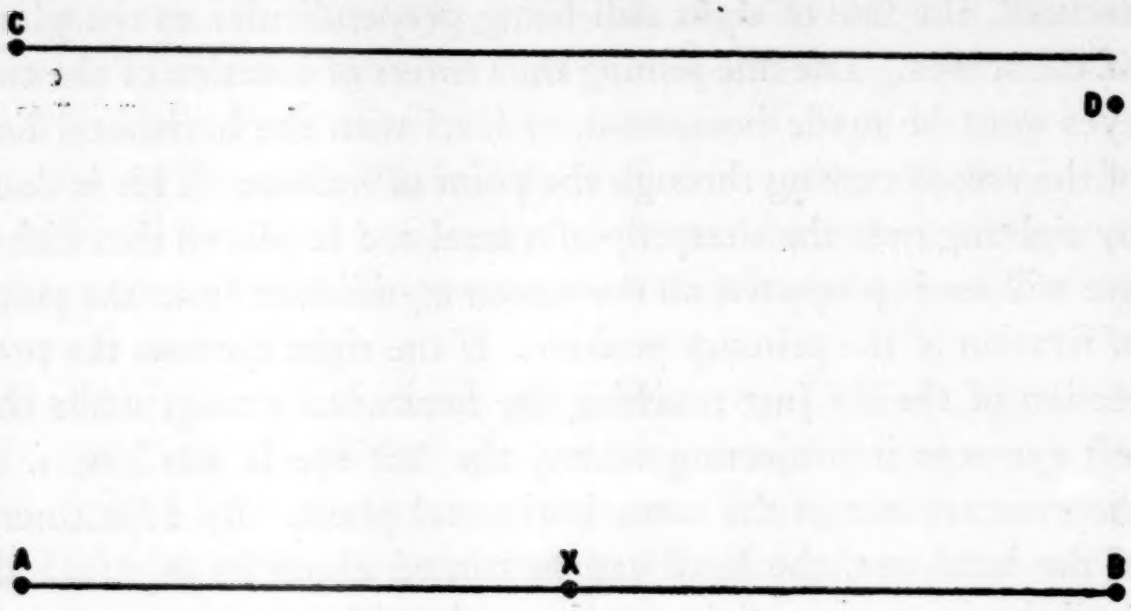


FIG. 1. *x*, point of fixation of primary position.

it is not parallel to *AB*. The median plane — that perpendicular to and bisecting the line joining the centers of rotation — cuts the screen to the left of *X*. That is, the point of fixation of the primary position does not necessarily fall in the median plane. If this be the correct explanation, rotation of the head to the right about the vertical axis should cause *D* and *F* to approach the horizontals. This actually occurs, an angular rotation of a half degree being sufficient to produce noticeable

changes in position. When *D* and *F* touch the horizontals, the eyes are level not only for *AB*, but for any horizontal line on the screen. In other words, the line joining the centers of rotation is now parallel with the horizontals of the screen, or the median plane intersects the screen at *X*. The amount of rotation necessary to secure this result measures the distance of the median plane from *X*. This is done by arranging a "sight" on the headrest so as to fall in the line of sight between one eye and *X*. After rotation this "sight" will indicate the position of the line of sight on the screen, and knowing the distance of the eye from the screen, the angular rotation is easily computed. Only with three subjects, Nos. 2, 4, and 5, did the point of fixation of the primary position fall within the median plane; with subject 1, it was located 3° 27′ to the right, and with subjects 3 and 6, 2° and 4° 55′ respectively to the left, of this plane. These results are contrary to the statement of Foster (Textbook of Physiology, iv, p. 140), that when in the primary position the visual axes of the two eyes are parallel to each other and to the median plane.

The positions of these zero points in relation to the primary point of fixation and to the median plane are represented in Chart I, where, as in the following charts, all distances on the screen are represented in their relative proportions. The line *AB* represents the perpendicular distance from the eye to the screen, the lines $x'y'$, x^2y^2, and x^3y^3, the intersection of the screen by the median planes. The circle-inclosed crosses 1, 2, 3, denote the points of fixation of the primary positions for the three subjects respectively, and the six crosses below indicate the zero points, *R* and *L* denoting those belonging to the right and left eyes respectively.

In No. 2 the zero points are really lines, *ab* and *cd*. The eyes were extremely sensitive to changes up and down; to the right and left, however, no movement could be detected within the distances represented by the lines. Weakness of eyes prevented any extended tests, or undoubtedly the length of the lines would

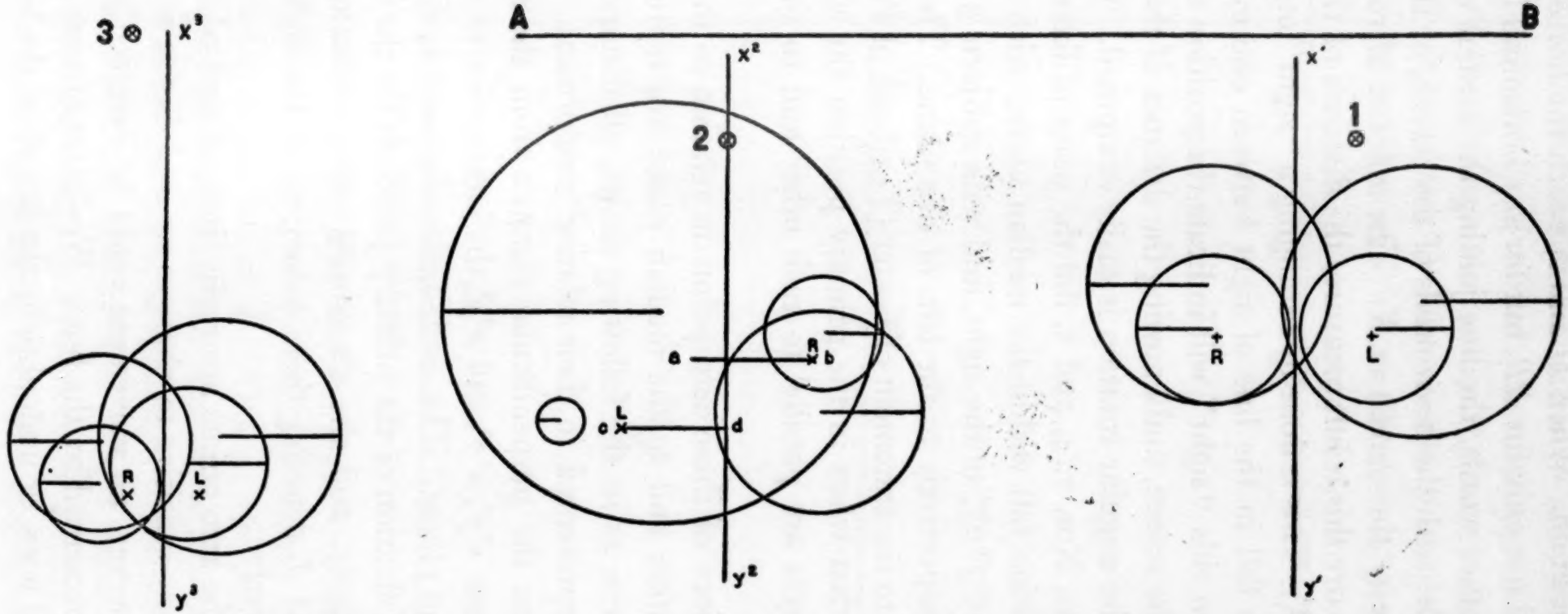


CHART I. 1, 2, 3, primary fixation points for subjects 1, 2, 3; x' y', x^2 y^2, x^3 y^3, median planes; *RX*, *LX*, right and left zero points; *AB*, distance of screen from subjects; large circles inclose all tangential variations; small circles inclose 75 % of tangential variations.

have been materially shortened, and at the ends away from the crosses. In subject 1, the eyes were extremely sensitive in the right and left direction, but less so in the vertical direction. In subject 3, the eyes were extremely sensitive in all directions.

These zero points are practically constants *for a definite distance of the screen*, i. e. *for a definite degree of convergence*. They were tested for a number of days in succession with no variations exceeding 2–3 centimeters. With subject 1, both the primary position and the zero points were re-determined after a period of four months with a slight difference in results. They were 3 cm. nearer the primary position and some 4 cm. further apart. These distances represent angular variations of approximately one half degree. It is possible that these variations may be explained by inaccuracies in the re-determination of the primary position in which no mathematical exactness can be obtained. In fact this position itself is supposed to fluctuate slightly from time to time. On the whole it is probable that the representation of these places of no movement as mathematical points is an ideal construction, and that they are really small areas of 4–5 cm. in diameter in which no movement can be detected, or within which the point varies from time to time.

It will be noted that the two points for each subject are practically equidistant from the median plane, though the distance differs in each case. They are all below the primary position, though again the amount varies for the three subjects. The two of each subject are at the same distance below with the exception of subject 2, where the discrepancy is slight. With subjects 1 and 3 the points are crossed as it were; the right zero point is to the left of the median plane, and the left zero point to the right. With No. 2, each point is on the same side of the median plane as the eye to which it belongs. Table I gives these relations in centimeter distances on the screen, and in angular terms in reference to the eye.

TABLE I. RELATION OF ZERO POINTS TO MEDIAN PLANE AND PRIMARY POSITION.

Relation of,	*Subject* 1.	*Subject* 2.	*Subject* 3.
Median Plane to Primary Position.	Left { 17.5 cm. / 3° 27′	Identical.	Right { 10. cm. / 1° 58′
Left Zero point to Median Plane.	Right { 22.5 cm. / 4° 26′	Left { 30. cm. / 5° 54′	Right { 10. cm. / 1° 58′
Right Zero point to Median Plane.	Left { 22.5 cm. / 4° 26′	Right { 25. cm. / 4° 56′	Left { 10. cm. / 1° 58′
Right Zero point below Primary position.	{ 57.5 cm. / 11° 12′	{ 65. cm. / 12° 38′	{ 135. cm. / 24° 58′
Left Zero point below Primary position.	{ 57.5 cm. / 11° 12′	{ 85. cm. / 16° 20′	{ 135. cm. / 24° 58′

The position of the zero points *on the screen* varies according to the distance of the eyes from the screen, *i. e.* it is a function of the degree of convergence. An object was fixed in a mechanism so that it could be slid along the line of sight between the eye and its zero point on the screen. A small screen was placed behind the object so as to insure better accommodation. The object was brought in near the winking eye, and gradually moved away along the line of sight to the zero point on the screen. Tests were made for all intermediate positions, and image movements always resulted, the amount growing less as the object approached the zero point. The position of the winking eye in the socket is thus constant throughout (with the possible exception of a slight rotation about the sagittal axis), the only change being in the position of the non-winking eye. And yet there is but one place where an image movement is not present. The only conceivable change in the winking eye is the *degree of muscular tension* due to the varying binocular convergence. The fact that these points are similarly placed in reference to the median plane would tend to show that they are a function of the convergent muscular tension.

The positions of the points on the screen for varying dis-

tances were then determined by moving the table toward the screen. With lessened distance, the positions approached the point of fixation of the primary position. The linear and the angular distances of the points below the primary position for five different distances of the eye from the screen are given for subject 1, in Table II.

TABLE II. POSITION OF ZERO POINTS FOR VARYING DISTANCES.

Distance from Screen.	290. cm.	247. cm.	217. cm.	173. cm.	117. cm.
Linear distance below P. P.	57.5 cm.	50. cm.	45. cm.	35. cm.	22. cm.
Angular distance below P. P.	11° 12′	11° 26′	11° 42′	11° 29′	10° 53′

P. P. is the point of fixation of the primary position.

The widest range of angular variation is but 49′, or about three fourths of a degree. The mean variation from a constant is but 13′. Any inequality in the level of the floor would introduce variations of this sort, and this, together with the impossibility of accurately determining the points within 2 or 3 centimeters, is sufficient to account for the variation.

The distance of the two zero points apart, or their distance to the right or left of the median plane, approximated a linear constant. A perpendicular line was drawn on the floor from the screen to two legs of the table. In moving the table, the legs were kept on this line, thus approximating the same relative position to the screen. Any variation in the position of the table would displace the points to the right or left on the screen. These shiftings on the screen never exceeded 5 cm., while the linear distances apart varied within 2–3 cm. of the 45 cm., as originally determined.

These determinations are confessedly rough, yet it seems certain that the distance below the primary position with varying distances of the screen approximates an angular constant, while the lateral distance from the median plane approximates a linear constant. These positions of the points on the screen

for the varying distances of the eye from the screen may be represented by fig. 2, where *X* is the point of fixation of the primary position, and *DE* the intersection of the screen by the median plane, and *RL*, R^1L^1, etc., the positions of the points as the distance of the eye from the screen is decreased.

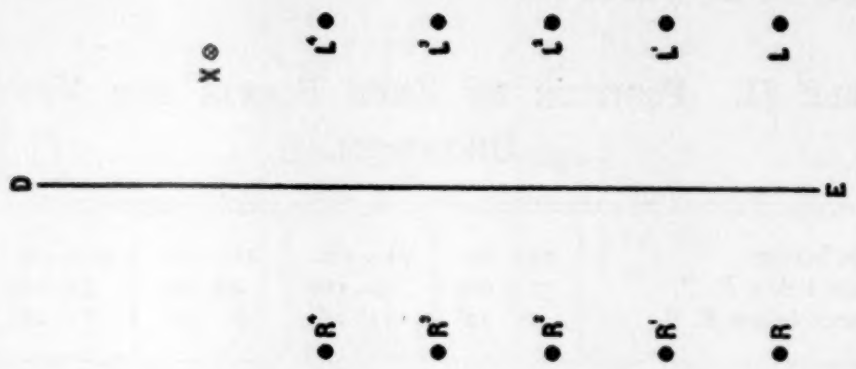


FIG. 2. *X*, point of fixation of primary position; *DE*, median plane; *R*-R^4 and *L*-L^4, zero points for varying degrees of convergence.

Summary: In three cases out of six, the point of fixation of the primary position was not in the median plane. It may fall to either side, the distance varying with individuals. The eyes are thus not necessarily similarly placed in the head when in the primary position.

In three cases out of six, zero points were present. These points are probably small areas whose position may vary slightly from time to time. In the field of regard there is but one point for each eye.

The two points for each individual are nearly the same distance below the point of fixation of the primary position. This distance is an angular constant for varying degrees of convergence, but varies in amount for the different subjects.

The two points for each individual are equidistant from the median plane. This distance is a linear constant for all degrees of convergence, but varies in amount for the different subjects. The points may be on the opposite or the same side of the median plane as the eye to which they belong.

The eyeball, when in the position where no image movement occurs, thus always remains in the same horizontal plane of

the head, but varies its position within this plane according to the degree of tensional convergence.

B. *Direction of Movements in reference to Zero Points.* Charts II and III represent the direction and extent of the image movements for each eye of subject 1. Since the point of fixation of the primary position was near the center of the screen, the zero points are located near the bottom. Consequently after their determination the head was rotated upward so that

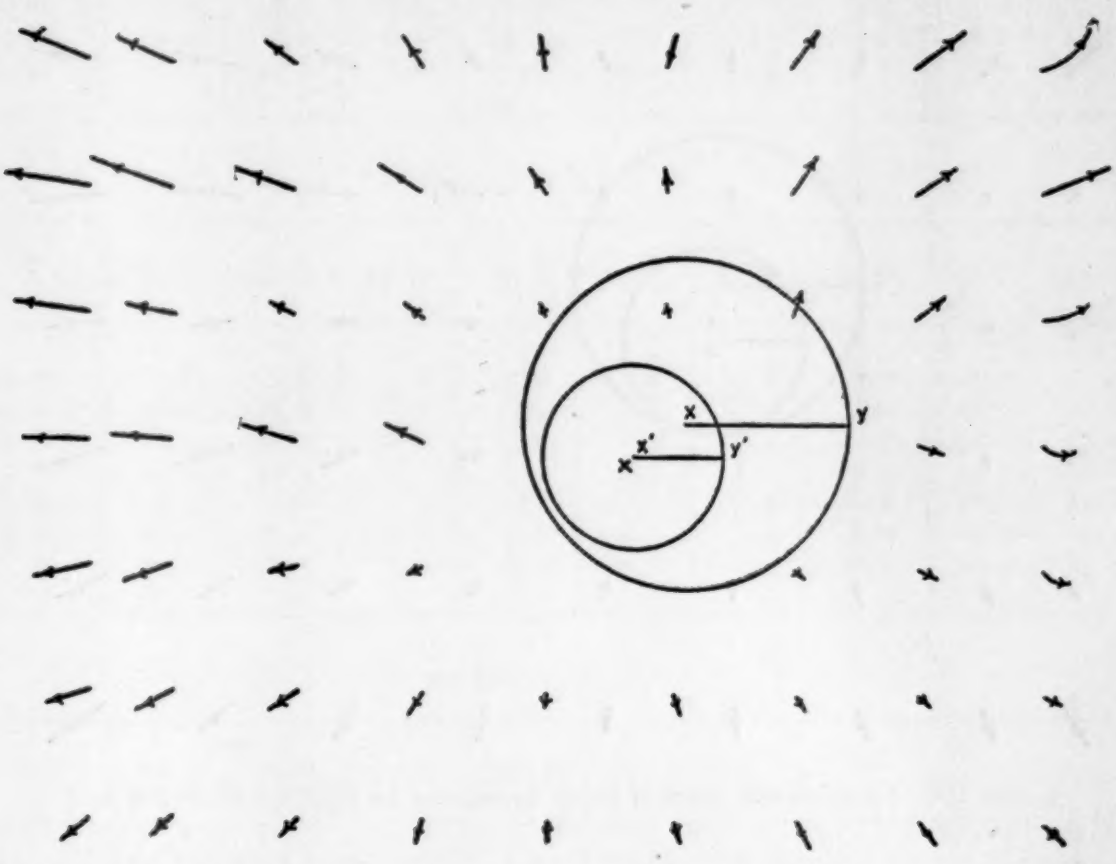


CHART II. Direction and extent of image movements for left eye of subject 1; x, zero point; circle xy encloses all tangential variations; circle $x'y'$ encloses 75% of tangential variations.

these points were near the center of the field. In this way it was possible to measure the movements on all sides of the zero points. The small cross denotes the zero point, and the arrowed lines represent the relative extent and the direction of the visual movements when that part of the screen is fixated. The directions, as may be seen, are away from the zero point to the peripheral part of the screen.

Knowing the horizontal and vertical components, the line

of direction of the movement is traced backward past the zero point, and the perpendicular, or shortest, distance of this point from the line of direction is determined. This perpendicular (*ad*) is called "the tangential variation from the zero point," and represents the direction of the movement in reference to the point (fig. 3). These tangential variations expressed in

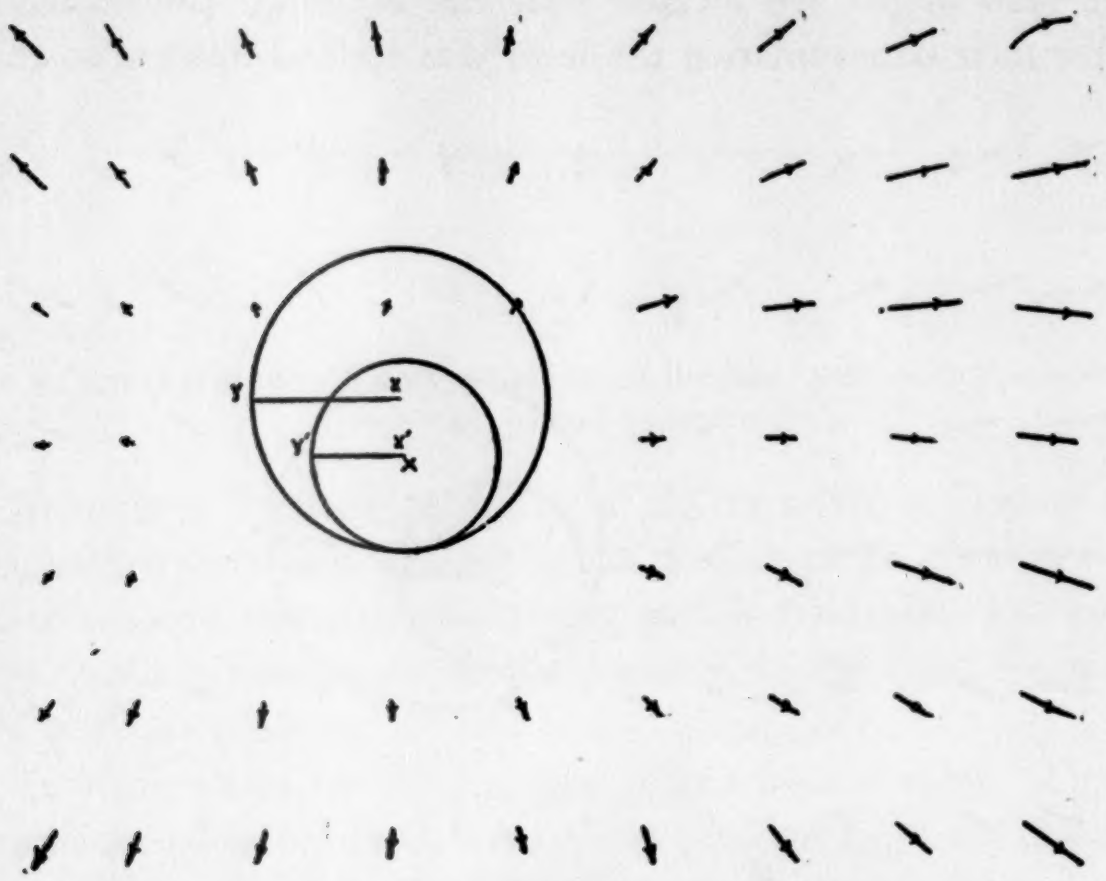


CHART III. Direction and extent of image movements for right eye of subject 1.

centimeters are given for three subjects in Table III. The top row of figures gives the distance of the fixated point to the right or left of the zero point, while the same values above or below are given by the left column. The table thus represents the spatial order on the screen of the various points fixated in reference to the zero point.

TABLE III. TANGENTIAL VARIATIONS FROM ZERO POINT.

Subject 1, L. E.

	130. L	110. L	80. L	50. L	20. L	10. R	40. R	70. R	100. R
95. A.	47.5	45.5	36.0	10.0	15.0	20.0	22.0	33.5	
65. A.	48.5	30.0	34.0	30.0	20.0	12.0	1.0	12.0	19.0
35. A.	21.5	23.0	5.5	4.0	9.5	11.0	30.0	16.0	
5. A.	5.0	2.0	15.0	17.0				35.0	
25. B.	9.0	7.5	20.0	7.5			4.5	5.0	
55. B.	14.0	5.0	10.5	13.0	10.0	7.0	12.0	8.0	14.0
85. B.	20.0	10.5	2.0	26.0	20.0	0.5	4.0	9.0	11.0

Subject 1, R. E.

	85. L	65. L	35. L	5. L	25. R	55. R	85. R	115. R	145. R
95. A.	1.5	7.5	3.0	4.0	1.0	19.0	25.0	43.0	
65. A.	20.0	19.0	18.0	5.0	1.0	15.0	33.0	41.0	46.0
35. A.	22.5	16.0	24.0	15.0	2.0	17.5	29.0	32.0	49.0
5. A.	5.0	10.5			2.5	5.0	5.0	16.0	33.0
25. B.	21.5	36.0				9.0	16.0	10.0	23.0
55. B.	21.0	34.0	23.0	5.0	4.0	0.0	6.0	14.0	23.5
85. B.	29.0	28.5	9.0	3.0	20.0	34.0	27.0	14.0	13.5

Subject 2, L. E.

	60. L	30. L	90. R	120. R	
100. A.	34.0			40.5	
70. A.		16.0	44.0		
50. B.		23.0	77.0		
80. B.	18.0			79.0	

Subject 2, R. E.

	115. L	85. L	35. R	65. R	
80. A.	6.0			33.0	
50. A.		35.0	29.0		
70. B.		18.0	19.0		
100. B.	11.0			9.0	

Subject 3, L. E.

	90. L	60. L	30. L	0	30. R	60. R	90. R
90. A.	13.0			23.0			2.0
60. A.			25.0		20.0		
30. A.		11.5				11.0	
0	18.0						34.0
30. B.		18.0				31.0	
60. B.			5.0		11.0		
90. B.	8.0			0.0			44.0

Subject 3, R. E.

	90. L	60. L	30. L	0	30. R	60. R	90. R
90. A.	10.0			0.0			15.0
60. A.			2.5		10.0		
30. A.		6.0				8.0	
0	42.5						0.0
30. B.		31.0				11.0	
60. B.			18.0		10.0		
90. B.	25.0			17.0			5.0

Some few of the lines of direction approach the zero point very closely. The variations are quite wide and irregular. Some comparisons among the six cases may be made by taking the smallest, the largest, the average, and the percentage of cases of 25 cm. and under. This latter value of 25 cm. has been chosen arbitrarily as it includes approximately 75 % of the cases, and hence will eliminate the extreme variables. These results are given in Table IV. Subjects 1 and 3 especially, and the right eye of No. 2 give quite similar and uniform results. The left eye of No. 2, however, varies markedly from the comparative uniformity. However, owing to extreme weakness of eyes in this subject but few measurements were taken, and these quite hastily, which facts may account for the variance. While these linear distances in centimeters may seem large, yet viewed as angular deviations in reference to the winking eye, they are

not so significant. The average variation expressed in such angular terms is within 3°–4°. 75% of the cases fall within 25 cm., or 4° 50′.

TABLE IV.

Subject.	1.		2.		3.		
Eye.	L.	R.	L.	R.	L.	R.	Average.
Smallest.	0.5	0.0	16.0	6.0	0.0	0.0	3.7
Largest.	48.5	49.0	79.0	35.0	44.0	42.5	49.6
Average.	16.5	18.0	41.0	20.0	17.2	13.2	21.0
Percentage 25 cm. and under.	79.0	75.0	37.5	75.0	81.0	81.2	71.4

These lines of direction of the image movements cut, of course, on all sides of the zero point, and apparently in an indiscriminate manner. The tangential variations, if drawn, would radiate out from the zero point in every direction like the spokes of a wheel. The extent of surface covered by these "tangents" may be represented by drawing the smallest circle which would contain all these radiating spokes. In other words, all lines of direction of the image movements would cut the circle. Two such circles have been determined and drawn for each eye, one embracing all the tangential variations, and the other those of 25 cm. and under. This latter circle would embrace 70–80 % of the cases, thus eliminating the extreme variants. These circles with their centers, x and x', and their radii $x\ y$ and $x'\ y'$ are drawn on the charts, graphically representing their relations to the zero point. They are all given together in Chart I, so that comparisons among the three subjects can easily be made. The actual distances in centimeters of the centers from the zero points and the lengths of the radii are given in Table V. With the larger circle, the results for subjects 1 and 3 agree fairly well. The centers of the circles are above the zero point in every case and to the right for the left eye, and to the left for the right eye. The size of the circles are fairly uniform

with the exception of the left eye of No. 2. With the series of smaller circles the results are still more uniform. The centers are above the zero point in every case. With the one exception of the left eye of No. 2, the size of the circles is nearly the same, and the distance of the center from the zero point is within 10 cm. With subject 1, the results for the two eyes are identical, the circles being of the same size and similarly situated in reference to the zero point.

There is no definite clockwise direction of these movements in reference to the zero point. The majority may be clockwise in one eye and non-clockwise in the other. No general rule prevails; in fact, for all cases the distribution in this respect is practically equal. However, the majority of the lines of direction cut above the zero point, the percentage being 65. Moreover, the fact that the centers of the smaller circles are situated above the zero points, but not to the same extent as the centers of the larger circles, shows that the larger variations also tend o cut above.

TABLE V.

	Subject.	1.		2.		3.	
	Eye.	L.	R.	L.	R.	L.	R.
Large Circle	Position of Center to zero point.	14. R.	2. L.	11. R.	2. R.	6. R.	8. L.
		10. A.	15. A.	34. A.	15. B.	17. A.	15. A.
	Radius.	40.	35.	62.	30.	35.	26.
Small Circle	Position of Center to zero point.	1. R.	1. L.	17. L.	3. R.	3. L.	8. L.
		2. A.	2. A.	2. A.	8. A.	9. A.	3. A.
	Radius.	22.	22.	6.	17.	23.	17.

The above linear values, however, do not fairly represent the relative variations, inasmuch as two places of fixation at different distances from the zero point may have the same tangential variation, and yet obviously the real variation from the zero point is markedly different in the two cases (fig. 3). The relative variation is best expressed in angular terms, the angle

made by the line of direction with the line joining the zero point and the place of fixation. Knowing the tangential variation

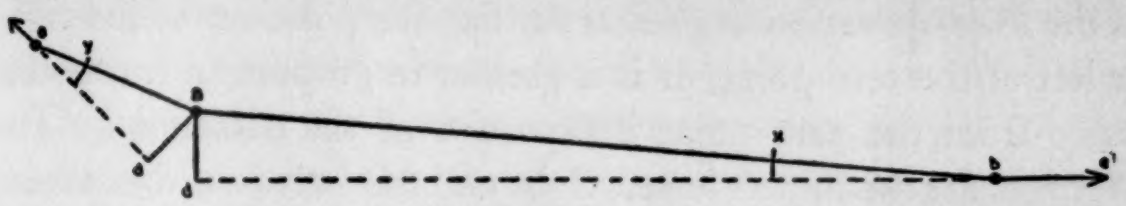


FIG. 3. *a*, zero point; *e*, *b*, points of fixation; *ef*, *bc*, image movements; *ad*, tangential variations; *x*, *y*, angular variations.

and the distance of the light from the zero point, the angular variant is easily computed.

These results in degrees are summarized (Table VI) by taking the smallest, the largest, the average, and the percentage of cases of 15° and under. 15° is an arbitrary value, eliminating the extreme variations.

TABLE VI. ANGULAR VARIATIONS FROM THE ZERO POINTS.

Subject.	1.		2.		3.		
Eye.	L.	R.	L.	R.	L.	R.	Average.
Smallest.	0.0	0.0	10.0	4.0	0.0	0.0	2.3
Largest.	34.0	31.0	48.0	28.0	27.0	28.0	32.6
Average.	10.2	10.6	22.5	12.7	12.0	9.0	12.9
Percentage under 15°.	76.7	74.0	37.5	62.5	69.0	87.5	67.9
Upper Half.	13.0	10.6	16.5	17.7	12.5	7.0	
Lower Half.	6.4	10.6	28.5	7.7	12.4	12.3	
Right Half.	10.3	9.7	29.5	16.0	13.5	5.8	
Left Half.	10.1	12.0	15.5	9.5	9.6	11.5	
125 cm. and over.	9.8	11.0			7.7	6.2	
75–125 cm.	8.3	9.7			12.0	10.0	
0–75 cm.	14.0	12.0			14.0	10.0	

Again with the exception of the left eye of subject 2, the results are comparatively uniform for the different eyes. The variations for a single eye are within quite wide limits, however. The lower limits are within 0–4°, and the upper within 27°–34°. The average variation for an eye is between 9°–13°.

These results may be averaged in reference to the position and the distance of the place of fixation from the zero point. Is the average variation greater for fixation positions to the right or left of the zero point, or is it greater in proportion to the distance from the zero point irrespective of the direction? The averages for the upper, lower, right and left halves of the screen, and for the distances of 0–75 cm., 75–125 cm., and over 125 cm. are given in Table VI. In subject 1, the average variations for the left eye are approximately the same in the right and left halves, while they are identical for the right eye in the upper and lower halves. The extreme variations are in the upper and lower halves for the left and right eye respectively of subject 1, but in the right lower and right upper quadrants for subject 2, and in the right half and left lower quadrant for subject 3. No general rule prevails in this respect which is applicable to all subjects. On the whole the extreme variations are for the shortest distances. This seems to hold for all eyes, though the tendency is more pronounced in some cases than in others. This fact may be partly due to a greater inaccuracy of measurement for the smaller movements, and also because the same linear error would introduce a greater angular variant in a small than in a large movement. The more probable explanation, however, is that fluctuations in direction occur more frequently at positions surrounding the zero points. It was mentioned that all observers noticed such fluctuations, which could be voluntarily controlled by the character of the eye closure. This control was extremely easy for positions near the zero point, but almost impossible for positions in the peripheral part of the field of regard. For near distances, the writer succeeded in varying the direction as much as 10°–15°.

Summary: Where zero points are present, the image movements for all other fixation positions in the field of regard are directed with more or less accuracy away from this point.

The lines of direction of the movements projected backward

cut on all sides of the zero point, the greater number and the larger variations going above.

The limits and average amount of the deviation from the zero point are fairly uniform for all subjects.

The deviation for each eye varies according to the position of the eye in reference to the zero point, but no general rule holds for all cases.

The deviation is greatest for the shorter distances of the fixation position from the zero point.

The image movement refers to the entire visual field of the winking eye.

C. *Length of Movements in reference to Zero Points.* As stated, the length of the movements seemed to bear some relation to the distance of the fixation position from the zero point. At this point no lateral movement is present, and as the fixation is gradually changed toward the periphery of the field of regard, the movements become larger and larger. This may be readily seen by an inspection of the Charts. The length of movement divided by the distance of the corresponding fixation position from the zero point should give percentage results approximating a constant for any eye, if any such definite relation obtains.

These percentage values are summarized in Table VII, by taking the smallest, largest, average, mean and mean variation for each eye. The amount of movement is practically the same for the two eyes of each subject. However, it is markedly different in the three subjects. The average amount is 2 to $2\frac{1}{2}$ times as great in No. 1 as in the other two subjects, while No. 3 shows a more pronounced movement than No. 2.

The limits within which the percentage values fall are quite wide, though the majority approximate a constant rather closely in Nos. 2 and 3, as indicated by the mean variation. The mean variation in No. 1 is quite large. However, the sources of error must be taken into account. Accuracy of measurement is difficult. The amount varies according to the character and in-

tensity of the winking, and it is difficult to maintain a constant and uniform method of judging as to where the perceived movement was interrupted by the lid, as the image becomes blurred and fainter, finally merging into a positive after-image. The attempt was made to avoid as much as possible all errors

TABLE VII. LENGTH OF MOVEMENTS IN RELATION TO DISTANCE FROM ZERO POINTS.

Subject.	1.		2.		3.	
Eye.	L.	R.	L.	R.	L.	R.
Smallest.	5.0	3.0	2.1	1.0	3.0	2.8
Largest.	20.0	15.0	5.6	6.4	4.6	6.2
Average.	9.3	8.4	3.4	3.3	3.9	4.3
Mean.	8.0	8.0	3.0	3.1	4.0	4.2
Mean variation.	2.7	1.8	0.9	1.3	0.5	0.75
Right Upper.	11.3	9.9	2.3	4.4	3.8	4.9
Left Upper.	11.7	7.1	4.2	3.1	3.9	3.6
Left Lower.	7.0	7.0	4.3	1.3	3.6	4.1
Right Lower.	6.0	8.6	2.6	4.4	3.9	4.7
125–175 cm.	9.25	10.2	[1]2.0	[1]2.0	3.8	3.9
75–125 cm.	9.4	8.1	[2]4.1	[2]4.7	3.4	4.4
0–75 cm.	9.0	7.6			4.3	4.5

[1] 100 cm. and over.
[2] Less than 100 cm.

from these sources. The amount also increased slightly by practice. Care was taken at each sitting to make a few preliminary trials. Again, variations may be due to the position of the eyeball in the socket together with the manner of winking. People differ in this latter respect; with some, the movement of the lower lid is largely responsible for the closure, while in others, the closure is performed almost entirely by the upper lid. If an observer varied his manner of winking from time to time, it is evident that the perception of the movement would be intercepted at relatively different periods after the initiation of the act, and consequently variations in length

would result. The attempt to maintain a uniform method of winking would tend to eliminate discrepancies of this sort.

Nevertheless, if the closure is produced mainly by means of the lower lid, it is evident that when the eye is rotated upward so as to fixate the upper part of the screen, the time elapsing between the beginning of the act and the covering of the pupil must be relatively longer than when the eye is fixating the lower part of the screen. Consequently the perceived image movements would be relatively greater in amount in the upper half of the screen. In other words, for every peculiar mode of winking some part of the screen is likely to be favored, the amount of movement increased at one place and relatively decreased at another. Fluctuations of this sort would be impossible to avoid. This emphasis of some part of the field over other parts would evidently be limited to the upper and lower halves. The right and left halves of the field could be little influenced by such a factor. However, if such a factor were present, its amount of disturbance would evidently vary according to the distance of the fixation position from the zero point. If movements for positions in the upper part of the screen were relatively increased in amount, and those in the lower half were relatively decreased, the extreme upper positions would be emphasized more than those just above the zero point, and the extreme lower positions would be affected more than those just below the zero point. In other words, assuming a definite constant ratio between the image movement and the distance of fixation position from the zero point, and assuming all other sources of error eliminated, still fluctuations from a constant result might occur both according to the position and distance of the fixation from the zero point. Of course the influence of such a factor in the results is a pure assumption, but possible. In fact, such differences in eye closure do exist, as may readily be seen by simple observation of a few cases, and the possibility of such a factor must be considered in interpreting the results.

Table VII gives the average ratio for all positions in the

four quadrants, and for the three distances irrespective of direction. Marked differences according to position evidently exist except for the left eye of subject 3. In the remaining cases, the amount of movement is greater in the right half of the screen for the right eye, and greater in the left half for the left eye.

That is, the movement for fixation positions in the temporal half of the field of regard is, as a general rule, relatively greater than for nasalward fixations. This tendency was so marked, that it was often noted during the course of the experiments. Obviously, peculiarities of eye closure are hardly a sufficient explanation, and it is more probable that we have to do with a fact representing differences of intensity in the conditioning physiological processes. Marked differences between the upper and lower halves are also present in subject 1, and in the right eye of subject 2. In the latter case, the paucity of measurements taken discredits any general statement, as the fact might be explained by incidental errors which would not be eliminated in the few tests taken. With the first subject, however, there is little doubt but that the movement in the upper half is relatively the greater, and as a matter of fact the eye closure in this subject is performed largely by means of the lower lid. Theoretically this peculiarity would account for the difference either wholly or in part, though it is possible that we have to do with differences in the intensity of the "corresponding eye changes." [1]

In the matter of distance, irrespective of the direction, from the zero point, the results allow of no general statement applicable to all cases. In subjects 2 and 3, the larger ratios are for the shorter distances, while the reverse is true for No. 1. It was noted that the mean variation from a hypothetically constant ratio was extremely high for subject 1. It is evident that the presence of this large mean variant in the left eye is due almost entirely to the difference between the upper and lower halves, while in the right eye at least 50% is due to the same factor of

[1] This term will hereafter be used to refer to the physiological changes in the eye which accompany or condition, as the case may be, these image movements

position. In other words, eliminating the factor of position, the values will approximate a constant pretty closely for all subjects. This is seen in the values for the three distances, especially for Nos. 1 and 3. The distance from the zero point varies from 25 cm. to 175 cm., yet the average ratio varies but little. The results of No. 2 are contradictory in this respect, for the average of the shorter distances is approximately 85 cm., and that of the longer distances is 130 cm. The corresponding ratios are 4.4 and 2.0 respectively, or the absolute extent of the movements is larger for the smaller distances. However the number of cases for this subject are too few to secure reliable averages, nor are they equally distributed among the quadrants so as to eliminate the factor of position which is of marked influence with this subject. It may be said that in the preliminary tests with this subject in moving the fixated light from the periphery of the field of regard to the zero point, the steady and gradual decrease in the extent of the image movement was at once noticed and commented upon. Consequently the writer has no doubt but that the subject conforms to the general rule, although the figures given do not demonstrate it. It is unfortunate that extreme weakness of eyes precluded any extended tests, as I have no doubt that more numerous measurements would give results similar to those of the other two subjects.

As stated, the ratio of movement varies markedly with individuals. Subject 1 exhibits a very pronounced movement. These individual differences may be due to either peculiarities of eye closure or intensity differences in the "corresponding eye changes." For instance, in some persons the eyelids are very wide apart and in others comparatively near together when the eyes are open. The time of closure may thus differ, and consequently the extent of perceived movement conditioned by certain eye changes running parallel to the lid movements must vary among individuals. The influence of such a factor is theoretically possible, but it cannot be considered as the sole factor, for while differences in the amount of "openness" among

subjects are clearly present, yet they do not exist to the same degree as the differences in movement.

Inasmuch as the movement refers to the whole visual field, objects situated at greater distances from the eye exhibit a more pronounced linear movement. Where a movement at this distance of the screen is 15 cm., objects in the line of sight at ten times the distance would move 150 cm. With subject 1, the image of a street lamp at the distance of a couple of blocks will jump clear across the street. The extent of movement is thus best expressed in angular terms with reference to the eye. The amount varies between zero and a maximum. The maximum values for the three subjects are 4°, 1°, and 1°–20′, quite noticeable amounts. Higher values could be obtained by choosing fixation positions nearer to the periphery of the field of regard.

Summary: The extent of the image movements varies markedly with individuals, but is approximately the same for the two eyes of any subject. The length bears some general relation to the distance of the fixated position from the zero point, and hence increases as the fixation is changed toward the periphery of the field of regard. It is greater in the temporal half of the field of regard than in the nasal half. It also varies slightly in the same eye according to the intensity and character of the closure.

2. *Cases with no Zero Points.*

The three remaining cases necessitate individual treatment. Subject 4 exhibits image movements with both eyes at this distance of the screen. Their direction is upward and inclined away from the median plane. The movements for two fixation positions similarly located in relation to the median plane are similar in direction and approximately equal in length. The median plane thus divides the field into two similar halves. The length of the movement is small, the average being about 3 cm., or less than a degree. The extent varies according to the

fixation position, being much greater in the upper half of the screen. The two eyes are similar in all respects. The facts that the movements are directed upward, and that their size decreases as the fixation is moved downward, would suggest the presence of a zero point in the extreme lower part of the field of regard. None was found, although the field was explored far below the screen.

Subject 5 at this distance of the screen exhibited image movements only with the left eye. Their direction is upward and to the left, varying from nearly straight up to straight left. The average length of the movements is 7.3 cm., ranging in angular terms from 19′ to 2.5°. The amount is smallest in the left upper corner, and increases in amount toward the left and bottom of the screen. The right eye of this subject exhibited no movements of any sort at this distance of the screen. However, with far fixation, *e. g.* a street lamp a block away, lateral movements occur. That is, the presence or absence of the phenomenon with this eye depends upon the degree of convergence. The distance of the object necessarily precluded any accurate measurements. The direction was always toward the right and upper part of the field of regard, the angle varying according to the position of the fixated object in the field. Thus the movements when present are similar in direction to those of the left eye, the statement being for this subject that the directions are toward the upper and temporal part of the field of regard. As nearly as could be judged, the amount of movement was also the same for the two eyes.

Subject 6 presented a further peculiarity in the fact that no movements occurred for either eye at this distance of the screen. With far fixation, *i. e.* with an approximately parallel convergent fixation, movements were present for both eyes. Their direction and extent were similar for the two eyes. The direction was toward the temporal part of the field and generally inclining slightly below the horizontal, the angle of inclination varying with the position of the fixated object in the field. The length

of the movements was quite small, but varied according to the fixation position.

3. *General Summary.*

These movements are evidently conditioned by the following factors: —

1. The position of the eyeball in the socket. The length and direction of the movements with all subjects and their occurrence with three subjects depended upon the position of the fixated object in the field of regard, *i. e.*, upon the position of the eye in the socket. The influence of this factor is very marked.

2. The degree of convergence. This factor controlled the occurrence of the phenomenon in subject 6 and in the right eye for subject 5. Since the position of the zero points varies for convergence, and the direction of the movements has reference to these positions, it may be said that convergence influences the direction of the movements to some extent. The absolute length of the movements varies with convergence; whether this is true for their angular amount was not determined. The influence of the convergent factor may also be argued from the similar location of the zero points in reference to the median plane, and from the general similarity for the two eyes.

3. The character of the closure conditions the direction of the movements.

4. The intensity of the closure influences the length of the movements.

5. Practice increases the length of the movements for a sitting. This was particularly noted with subject 1. For the same position the movement would be longer after a few minutes' practice. No increase could be detected after the first few minutes, nor for daily practice.

IV. Lateral Movements due to Binocular Closure.

So far we have described the lateral displacements of the monocular field due to the closure of the corresponding eye.

With binocular closure, both fields move simultaneously, each field moving apparently in the same general direction and to the same extent as in monocular closure. It will be noticed that with the first four subjects, the directions of the movements for each field for monocular closure are nearly identical for the same fixation points. This is necessarily true, for each movement has a reference to its own zero point, and these are situated relatively close together. Hence with binocular closure, the two fields move almost as a unit, diverging but slightly. With a large object the two images do not completely separate, but give the impression of a single object moving in a definite direction. Even here a slight divergence of the two images is evident from the fact that the binocular image of the object becomes larger and much blurred. This divergence of direction is easily noticeable by using a small object, *e. g.*, the electric light, for fixation. If the light be situated near the zero points, or if the movements be relatively large, the two images become completely separated. However, it is possible that the movement of each field with binocular closure does not have exactly the same direction as it would have under monocular conditions; it is possible that some slight modification of the direction of each field may result because of the simultaneous closure of the other eye. No definite answer can be given to the question because with binocular closure the lack of any stationary points of reference does not permit an exact definition of the movement directions. Hence any accurate comparison of the directions under monocular and binocular conditions is impossible. With such rough comparison as was possible, most subjects could detect no directional differences in the two cases. If there be any such "cross" influence with these subjects, it is evidently of small amount.

Such a "cross" effect was clearly evident with subject 5. It will be remembered that this subject exhibited with monocular closure only movements of the left field at this distance of the screen; the right field was entirely stationary except for far

distances. However, with binocular closure both fields moved as a unit, there being no separation of the images whatsoever. In other words, the closure of neither the left nor the right eye alone produced any effect upon the right field, while the simultaneous closure of both eyes caused it to participate in the movements. Clearly binocular closure must have been effective upon the right field. Moreover, the direction of this unitary binocular movement in nearly 50 % of the cases differed from that of the left field under monocular conditions by 45–80 degrees. That is, the closure of the left eye alone will produce movements of the left field in a certain direction. If the right eye participates in the closure, these directions are greatly modified, the modifications being large enough to permit of certainty in spite of the rough methods of comparison necessitated. It will be recalled that monocular closure of the right eye did produce movements of its field for greater distances of the fixated object, and that these movements were always directed upward and to the right. Now whenever this unitary binocular movement differed in direction from that of the left field with monocular closure, this deflection was always toward the right; it was as if the single binocular movement were a mean resultant of the two diverging monocular components. Thus we see that with this subject, binocular closure causes the right field to move when otherwise it would not, and, further, that this participation is clearly effective in determining the resulting direction in nearly 50 % of the cases.

Something similar to this would occur occasionally for subjects 4 and 5 with monocular closure. Instead of the normal separation of the two images, they would cling together, as it were, refusing to separate. In this case the fixated object and the whole binocular field would either remain stationary or else move as a whole. In other words, the image of the winking eye would cling to the stationary image of the non-winking eye, or else move as usual, but carry this latter image with it. Again the two images might move together for a short distance

and then separate; that belonging to the winking eye would then complete its usual movement, while the other would move back to its customary stationary position. Such phenomena as these were rarities, however, and were confined to the two subjects noted.

V. Lateral Displacements due to Finger Pressure.

These displacements due to finger pressure upon the globe are well known; it was found that these movements are similar to those of closure in all essential respects. The direction and extent of these pressure movements are conditioned (1) by the direction and intensity respectively of the pressure, and (2) by the position of the eye in the socket. The first factor is well known: with a given position of the eye the image movements may be greatly varied by the character of the pressure. The second proposition is equally true, although the influence of this conditioning factor is more apparent with some subjects than with others. Given a constant pressure, the character of the resulting displacement varies for different positions of fixation. For any one position it is much easier to produce a movement in some one direction, this direction varying with the position of the eye. With the first two subjects, it is much easier to produce a movement peripherally than centrally; in fact, for extreme peripheral positions it is almost impossible to produce a movement directed toward the center of the field of regard.

For the first two subjects it was found that a nasalward pressure exerted upon the temporal side of the eye would produce directional results entirely comparable with those of closure, *i. e.*, in a peripheral direction from the point of fixation. If the eye were turned to the right, the movement would be to the right; if the top of the screen were fixated, the movement would be upward, and so on. With subjects 5 and 6 this nasalward pressure produced movements whose directions were identical with those of closure for the majority of fixation positions, irregularity of direction otherwise prevailing. With

subject 4 the two series of image movements (pressure and closure) were never identical in direction, those resulting from pressure always being in the *same* general direction as the pressure movement itself, *i. e.*, to the left for the right eye and to the right for the left eye. With the left eye of subject 3, the two series were generally identical in direction, and where this was not true the pressure directions varied markedly to the left, — a direction *opposite* to that of the pressure. For the right eye of this subject, the two series were never identical, those resulting from pressure being toward the right — a direction *opposite* to that of the pressure — and varying from 30 to 70 degrees downward.

VI. Lateral Displacements due to Suction.

Suction produces the same visual phenomena as does winking or pressure. The test was made upon the right eye of subject 1. An air-tight sealing wax cage with a glass front was constructed so as to fit tightly over the bony structures of the nose, cheek, and forehead. No pressure was exerted upon the eyeball. The cage was fitted with a stop-cock tube connecting with the outer air, and the inside pressure was lowered by exhausting air through the tube. No registry of the external air pressure was made, but it was sufficient easily to maintain the weight of the cage.

The visual phenomena were identical with those of winking or of nasalward pressure for this subject. The amount of the displacement increased in proportion to the amount of air exhausted from the cage. The direction and extent of the displacement were again conditioned by the position of the eye in the socket. For each position of the head in reference to the screen, there is one and but one fixation position where an object can be seen single. This position of unitary vision would correspond to the zero point, because there is no displacement of the field for this position. For all other fixation positions, all objects are doubled, *i. e.*, the visual field of the

right eye has been displaced. The direction of these displacements is always peripheral to the spot giving unitary vision (zero point). Still keeping the head in a constant position, rapid rotation of the eye causes pronounced movements of the displaced field, *i. e.*, because the direction of the displacement is conditioned by the position of the eye in the socket. Changes in the position of the head in reference to the screen also produce lively movements in the displaced field, because the position of possible unitary vision (zero point) is thus changed, and the direction of the displacement has reference to this point.

It is a noteworthy fact that winking produced no image movements when the air pressure was much reduced. This would seem to indicate that suction produces the same eye changes as does closure. As the air pressure is gradually decreased, the conditioning eye changes are gradually increased in amount, and consequently closure has less and less effect. Finally the amount is increased beyond that produced by closure, and hence this latter force has no appreciable effect. The phenomenon is hardly explicable in other terms.

The subjective eye feeling is somewhat different from that of pressure or closure. There is a marked feeling of strain located in the lower part of the socket near the nose, as if the fatty masses within the socket were being sucked outward at this spot. Besides this there is a disagreeable strain all over the eyeball, quickly leading to retinal fatigue. This latter is also characteristic of both closure and pressure, which are extremely fatiguing and cannot be continued for more than an hour's period a day without leading to serious results. The subjective feeling in these cases gives no clue to the nature of the accompanying eye changes, with the exception that if they be eye movements of any sort they are plainly different in character from normal rotations.

VII. Lateral Displacements during Normal Rotations.

These lateral displacements of the visual field occur occasionally in normal rotations for the writer. They are always present in extreme rotations to the peripheral parts of the field of regard. In the right upper part of the field, objects cannot be seen single under any circumstances. The right eye is here affected, its image moving above and to the right of the object. To the left of the field, the right eye's image of the object moves to the left. Similarly the same description applies to the left eye for the left upper and the right parts of the field. Rotating below, the face intercepts the vision before any displacement effects are noticeable. The direction of the displacement is thus determined by the position of the globe in the head. Again the movement is directed away from the object and toward the periphery of the field. After the eyes have rotated sufficiently to produce any effect, a further rotation in the same direction gradually increases the displacement in amount.

Fatigue noticeably influences the occurrence and the extent of the movements. The attempt to hold the eyes in the extreme peripheral positions is very fatiguing, and the displacement gradually increases in amount as the fatigue sets in. Furthermore fatigue will cause the appearance of these displacements for fixation positions where normally they do not occur. At first the object will appear single, but after a few minutes' continual fixation one image will begin to separate from the other, and to move gradually away for 5 to 15 cm. Once separated, these images cannot be voluntarily combined except by rotating the eyes to the central portions of the screen, and then returning to the object. At first these displacements occurred for the right eye in the right upper part of the field only for positions at least 45 degrees distant from the primary position. During the course of a long period of experimenting in these positions, in which the right eye had become extremely fatigued, this distance was reduced from 45 to 20 degrees.

In these cases where the movements occurred during the fixation because of the oncoming fatigue, one introspective result is significant; the right eye felt as if it were being rotated back toward the center of the screen, *i. e.*, in a direction opposite to that of the image displacement. This movement felt like a normal rotation. This subjective feeling was very striking, and, as noted, very different results were obtained with winking, pressure, and suction. The significance of these observations will be discussed later.

VIII. Sagittal Rotations of the Visual Field.

The visual field while undergoing lateral displacements may also be slightly rotated about the line of sight. This phenomenon is easily produced by pressure, and is best observed by

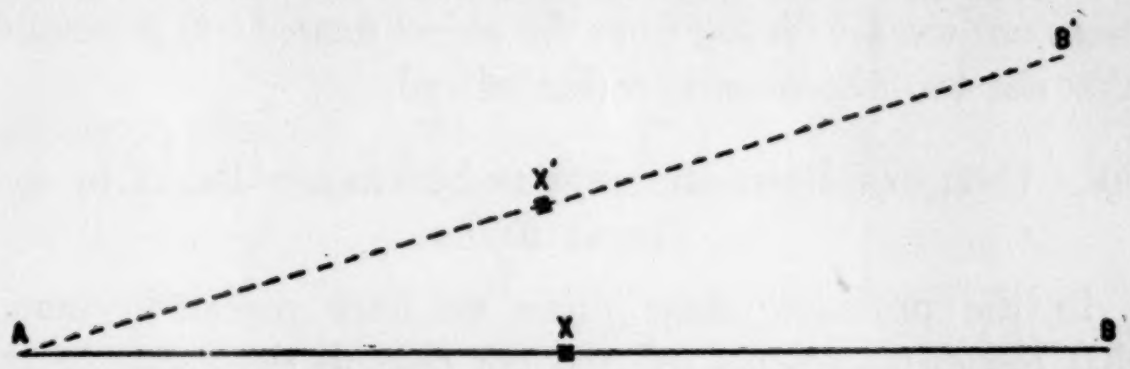


Fig. 4. Rotation of visual field; X, point of fixation; $AX'B'$, displaced image of AXB.

noticing the system of white lines on the screen. The appearance is represented in fig. 4, where the line AB is the image belonging to the stationary eye, and X is the fixation point. The center of this rotation, A, is not at the point of fixation, but at the extreme edge of the visual field, at times even falling outside; it may be on any side of X, either to the right or left, above or below. The direction of the rotation may be in either direction about A. With pressure the position of A in reference to X, and the direction of the rotation seem to be functions of the character of the pressure and the position of the eye in the socket. With winking the phenomenon is most often present with fixation positions in the periphery of the field of regard.

Closely associated with the above is the fact that these lateral

movements are not always straight, but slightly curved. This phenomenon was confined to a few subjects, and then occurred only for extreme peripheral fixation positions. Several cases of these curved movements are represented in the Charts. This curvature is constant in occurrence and character for any given position. Moreover, for any eye the curvature seemed to be constant in direction, *i. e.*, the movement would be deflected in either a clockwise or non-clockwise direction in reference to the primary position. Such movements occurred so rarely with closure that it is hardly possible to make any general statements regarding them. With pressure such movements can be produced at will by gradually varying the direction of the pressure. A curved movement of this kind would result from the rotary phenomenon described above if the center of rotation were not too far distant from the object fixated. It is possible that the two phenomena are thus related.

IX. Unequal Displacements in different Parts of the Visual Field.

In the preceding descriptions we have repeatedly stated that the displacements referred not only to the image of the object fixated, but to all images, to the field as a whole. While this is true, yet all the images in any one displacement do not move to the same extent or in the same direction. Our previous descriptions and measurements as to the direction and length apply only to the center of the field, — to the image of the fixated object. Images of other objects may move more or less than this, and in a different direction. This inequality of movement for different parts of the field occurs for all displacements due to closure, pressure, suction, or extreme rotations; it occurred for all subjects, for all fixation positions, and for all directions of displacement.

The phenomenon presents certain constant characteristics which are represented by fig. 5. Let the solid squares (*A*–*I*) represent objects on the screen situated at equal distances from

each other. Let the unshaded squares (*a–i*) represent their corresponding images belonging to the right eye after a displacement in any direction. The arrow represents this direction, and *E* is the object fixated. It is evident that the images *a*, *b*, *c* have moved further than *d*, *e*, *f*, and these latter more than *g*, *h*, *i*. The images situated in the extreme peripheral portion of the

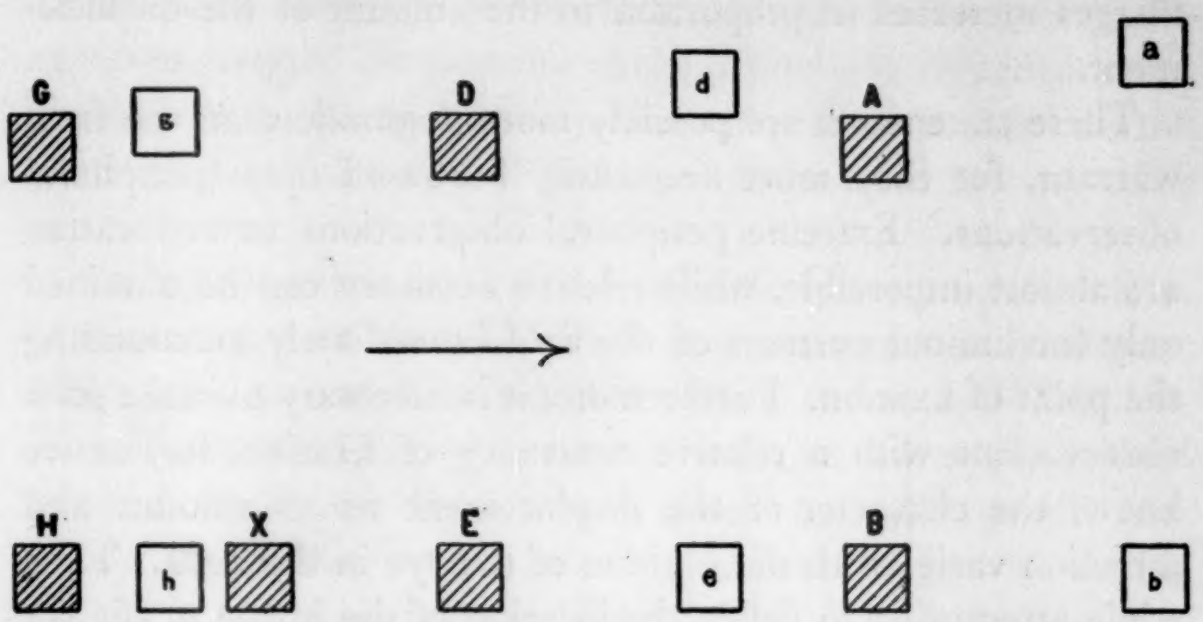


FIG. 5. Unequal displacement in different parts of the visual field; *A–I*, objects; *a–i*, displaced images; *E*, fixated object.

field toward which the movement is directed have undergone the greatest amount of movement; images lying in the extreme parts of the opposite side of the field have suffered the least displacement; all images situated between these two extreme positions have moved proportionately to their intermediary location. Besides, the field has spread out perpendicularly to

the general direction of movement, the amount of spreading being greatest in that part of the field toward which the movement is directed. The images *d* and *f* have thus moved apart, but not to the same extent as have *a* and *c*. Consequently *a* has not only moved more than *i*, but in a slightly different direction. The amount of this inequality of the movements of any two images increases in proportion to the amount of the displacement.

These statements are possibly more dogmatic than the facts warrant, for they must necessarily be based upon peripheral observations. Extreme peripheral observations as to location are almost impossible, while relative accuracy can be obtained only for limited portions of the field immediately surrounding the point of fixation. Furthermore, it is necessary to make such observations with a relative constancy of fixation, for, as we know, the character of the displacement as to amount and direction varies with the position of the eye in the head. Thus while attempting to define the location of the image *a*, (fig. 5) any involuntary rotation of the eye toward *a* will immediately change the character of the displacement, *i. e.*, alter the location of *a*, the very thing we are attempting to determine. This alteration of the displacement will be different for every image because the induced eye movement will be different; hence it is possible that these inequalities may be mere artifacts, resultants of the reflex eye movements involved in peripheral observations. As a matter of fact this supposition would be true for subjects having zero points; the reason for this will be given later. In these cases any rotation of the eye during the maintenance of pressure (a superimposed rotation) causes a slight additional movement of the displaced field, whose direction is the same as that of the rotation. Hence during the observation of *a*, if the eye be rotated in that direction from *E*, the image *a* must move in the same direction, *i. e.*, upward and to the right; likewise *c* would move down and to the right, or in observing *h*, the movement would be to the left, etc. Hence the distance *A–a* will

appear greater and the distance *H–h* smaller than the primary displacement we are attempting to measure. Relative constancy of the fixation during the observation is thus absolutely necessary. However, in stating the general conclusions above, we have been keenly cognizant of these difficulties. This appearance of inequality of movement for different parts of the field was early noticed and carefully observed throughout the course of the experimentation. At first the phenomenon was regarded as an illusion, or artifact, resulting from imperfect control of the fixation. Careful tests and observations have led to a rejection of this view.

To localize accurately these displaced images, the white lines of the screen were covered with neutral gray paper so as to avoid all possible means of orientation as to distance and direction. The objects used (fig. 5) were small squares of brightly colored paper. An electric light was so placed as to secure the best conditions of illumination for each displaced image. A similar object *X* was placed 20 cm. distant from *E*, and the field was displaced by pressure, so that the displaced image of *X* coincided with the stationary image of *E*, *i. e.*, the field was displaced 20 cm., or approximately 4 degrees. It is necessary to use pressure in order to control the direction and the extent of the movement. Under the subject's direction, an assistant moves a distinctly visible pointer over the screen until it coincides with the observed image. This position is marked, and the other images are located similarly. During the test the pointer was given a slight vibratory movement so as to render it more distinctly visible. The test can be continued as long as desired, moving the pointer backward and forward on all sides of the image until the subject is confident of their coincidence of location. During this time it is impossible to inhibit all involuntary movements in the direction of the eccentric point of interest. With practice, however, they can be largely minimized, and the subject only needs to be confident that the localization obtained represents the facts during the periods when the fixation is rela-

tively stationary at *E*. After all images are localized, other directions of displacement may be taken, and then the whole series may be repeated as often as is thought necessary.

The peripheral objects must be placed as far as possible from *E*, without falling outside the zone of accuracy of localization. After a number of preliminary tests, subject 1 found that the objects (fig. 5) could not be placed more than 40 cm. (7–8 degrees) apart for confident judgments. With these conditions, and for a displacement of 20 cm., the following results were obtained as an average of a series of nine localizations: *h* moved 18 cm.; *x*, 20 cm.; *e*, 21 cm.; *b*, 23.5 cm., a discrepancy of 5.5 cm. for the two extremes; *g* and *i* had moved 3 cm. apart, while *d* and *f* had diverged 7.5 cm. No satisfactory localizations of *a* and *c* could be made because they had moved outside the zone of accuracy. If *HB* and *DF* represented horizontal and vertical lines 80 cm. in length, it is evident that their values after displacement would be 85.5 and 87.5 cm. respectively. If the initial displacement were greater than 20 cm. these discrepancies would be correspondingly increased.

Hence our general characterization of the field as a whole is true for its central portion at least, provided that the results are not due to reflex eye movements. Several considerations disprove this assumption, however. As was said, it is not necessary to eliminate these movements entirely; one needs but to be confident that the localizations made represent conditions during the periods of constant fixation. With practice the writer became quite proficient in inhibiting these reflex movements, and also extremely sensitive to their occurrence. One can detect these fluctuations in the position of the fixation point unless they are extremely rapid or relatively slight in extent. Moreover, the conditions of the test offer additional means for their detection: The finger tips are firmly pressed against the lids, and as a consequence a very slight rotation is immediately felt. Since these discrepancies are the result of eye movements according to the hypothesis, the image observed must be shifted at least

3–4 cm. during the movement in order to account for the discrepancy. As will be shown later, this additional displacement of the image is due to an actual shift of the stimulus over the retina, and, as is known, the peripheral portions of the retina are extremely sensitive to movement. Now in attending to these images one ought to be conscious of any movement of such proportions; in fact, one does sense such a shift whenever the eye actually moves. Consequently the immobility of these images during the observation proves either that the fixation has remained relatively constant, or that the eye deviations which do occur unnoticed are not sufficient to produce the discrepancy noted. Moreover, if this hypothesis were true, not only the image observed, but also the displaced image of *X* must be shifted 3–4 cm. In other words, *x* would no longer coincide with the object *E*, a fact which should be easily observed. Again, to produce this extra displacement of 3.5 cm. for the image *b*, the eye must move at least 40 cm., *i. e.*, from *E* to *B*. This follows from Table VII giving the ratio between the displacement and the fixation position for closure. As a consequence, the same ratio must obtain between the difference of two displacements and the distance between the two corresponding fixation positions. For subject 1 this ratio is approximately .08. That approximately the same conditions obtain for pressure can readily be demonstrated; one can measure the amount of eye movement necessary to produce any given amount of this extra displacement. To claim that under these conditions such fluctuations of the fixation point (40 cm.), or eye rotations of 7–8 degrees, can occur without detection is preposterous. These localizations were also made by one subject (S. J. McC.) with whom zero points were absent. Consequently eye movements could not have produced the phenomenon in this case. The truth of the proposition is again evident by arranging the test as in fig. 6. *AB*, *CD*, *EF* are three vertical lines on the screen 10 or 15 cm. apart. *X*, *Y*, *Z* are three small paper squares. The field is displaced upward by pressure so that the displaced

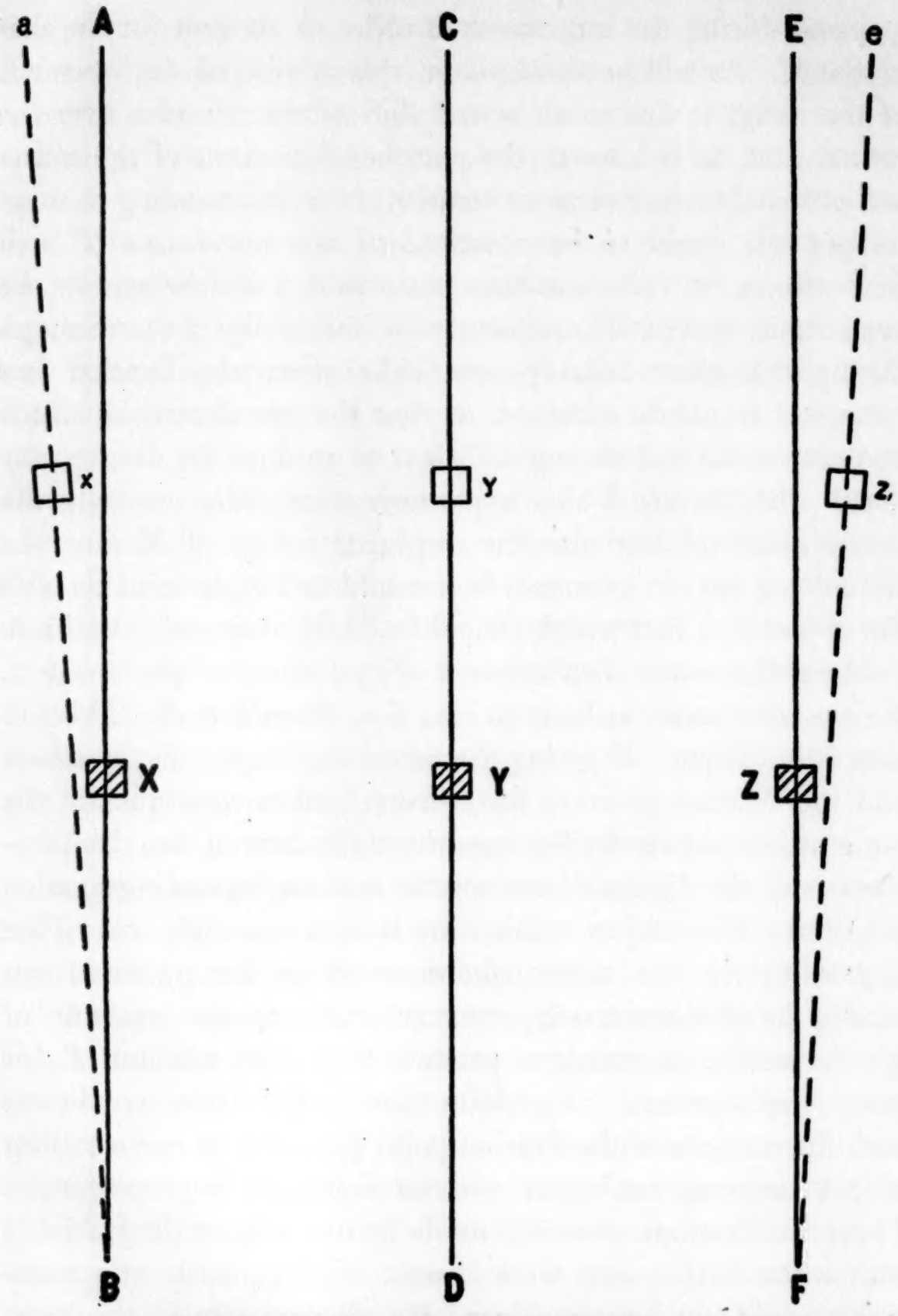


FIG. 6. Unequal displacement in different parts of the visual field ; *x*, *y*, *z*, displaced images of objects ; *aB*, *eF*, displaced images of lines.

image *y* falls on the line *CD*. The eye is rotated so as to fixate *y*. The images *x* and *z* are so near together that they may with practice be observed simultaneously, and they both fall outside

of the lines *AB* and *EF*. If the observation is simultaneous, it is evident that eye movements cannot account for their divergence.

If the displaced images be tinted by holding a strip of colored gelatine paper before that eye, the lines *aB* and *eF* can be readily discriminated, and they will have the position shown in the figure. The divergence begins toward the bottom of the screen, and gradually increases in amount toward the top. Since the phenomenon is gradual and continuous, it can be followed much farther toward the periphery than otherwise. One certainly gets the impression that the phenomenon is applicable to the field as a whole, and not merely to a limited portion of its center.

X. Changes in Size, Form, and Brightness of the Displaced Images.

By comparing a displaced image of a colored paper object with its stationary correspondent, a noticeable decrease in brightness is evident. The color has a faded and washed out appearance; the surface is confused and blurred; the contour of the image is not sharp and distinct, but vague. This decrease of brightness is not due to the fact that the image is perceived peripherally, for by a slight rotation it may be perceived foveally, while the stationary image is seen peripherally; nevertheless the decrease of brightness is still apparent. With binocular closure where the two images are not separated, but only slightly doubled, this blurring and confusion of the outline and surface is quite apparent.

Changes in size and form are closely related to the inequalities of movement formerly described. In fig. 5, if the square bounded by the objects *A*, *C*, *G*, *I* were considered as a single object, it is evident that its displaced image *a*, *c*, *g*, *i* would be considerably modified in both size and shape. According to this the image should increase in size, although, as we shall see, judgments based upon the mere appearance of the image give contrary results.

Changes in form were detected only by a few observers, and then only occasionally. Such changes are not readily apparent except by very careful scrutiny and during large displacements. The observed variations were similar in nature to those which would be logically supposed to follow from fig. 5. The sides of a square object would often shrink near the middle, becoming concave in appearance. If a square were displaced in the direction of one of its diagonals, it would become elongated along that diagonal, the sides would hollow out, thus presenting a diamond-shaped appearance. With binocular closure, changes in form are more evident because of the slight doubling of the two images.

The monocular image became smaller with all subjects. These results are not based upon measurements, but represent the apparent size. This decrease in size also occurred at the zero points where no lateral movements, and hence no inequalities, are present. The concavity of the sides noted above is a symptom of this general shrinking appearance. The phenomenon is probably due to a great extent to the decrease in brightness and the confusion of surface and contour.

The binocular image increased in size for the first two subjects, occasionally appeared smaller with one subject, and in the other cases no change was noticeable. The doubling of images in binocular closure will account for this, it being sufficient either to overcome or neutralize the apparent decrease of its monocular components.

The observed decrease in the brightness and the general effect of blur are apropos to the controversy as to whether in binocular vision the intensity of the two visual processes are fused, or combined, into a single resultant greater than that of either component. Do we see an object with two eyes as brighter than we do with one? Piper[1] has considered this question in two recent papers, giving the statements and results of Fechner, Aubert, Helmholtz, Hering, and Schenck. These authors

[1] Zeitschr. f. Psychol. 32, S. 161.

showed no agreement on the point in question, though the consensus of results seemed to favor the summation hypothesis. Aubert and Fechner maintained the affirmative to be true in the majority of cases. Piper in a series of experiments maintains the opposite doctrine. In a review of Piper's article, the opinion was ventured that this discrepancy of results was due to the different methods used, and that Piper's method and results must be regarded as the more reliable.

Piper used two objective intensities which could be varied in a determinate manner. The head was so adjusted that one object could be seen binocularly and the other monocularly. Direct comparisons were thus made with a slight eye rotation. Aubert and Fechner used but one object which was fixated binocularly, and then one eye was closed or covered and comparisons made. The majority of subjects noticed a decrease in brightness at the moment of closure, a slight shade or shadow passing over the object. However, some subjects noticed no change whatsoever. These results are identical with those noted in these experiments. On closure the object becomes slightly doubled, and consequently indistinct and confused with most subjects. The image of the winking eye becomes blurred, less bright, and less distinct in outline. Consequently in so far as Aubert's and Fechner's results are based upon judgments made after eye closure, they are faulty because it is probable that these changes occurring during the closure must have influenced the judgments. There is little doubt but that the slight shade passing over the object is due to the doubling. Piper's method at least avoids the possibility of any such errors.

XI. Third Dimensional Movements.

For the sake of clearness of treatment these image movements have heretofore been described as lateral, *i. e.*, within the plane of the screen. This is not strictly accurate, for they sometimes involve a more or less pronounced third dimensional component. The displaced image not only moves sidewise, but also nearer to

or farther away from the subject. This phenomenon differs so markedly among subjects that an individual treatment is necessitated.

Subject 1. With monocular closure, the movements may have a backward component of 4 to 5 inches. The extent of this component varies for the different fixation positions. For peripheral positions where the lateral component may be 25 cm. in length, the backward component may be easily overlooked. As the fixation is changed toward the zero point, the lateral component gradually decreases in length, and hence the backward component becomes more noticeable. At the zero point the lateral component is absent, and the movement is directed straight backward. With binocular closure, this component is larger and more noticeable. At a position midway of and a trifle above the two zero points, the lateral movement is absent and the field moves backward for a distance of 9 to 12 inches. The largest movements occur at this central position of fixation. The extent of this component has only been estimated, as no means of accurate measurement have been devised. Apparently not all parts of the field participate equally in this movement. The field appears to be bulged backward along the line of sight, presenting a concave appearance. Especially is this true for binocular closure with central fixation positions. This backward movement is as real, subjectively considered, as any objective movement can be. With rapid squinting the screen sways backward and forward in rapid vibration like the bellying of a sail in the wind. The absolute extent of the movement varies directly with the distance of the object from the observer. For near distances it disappears entirely for monocular closure, and for near peripheral positions with binocular closure. For the central positions with binocular closure, the backward movement decreases in size with convergence, then vanishes, and is finally directed forward, or toward the subject, when the fixated object is brought within a distance of less than two feet from the subject. Backward movements are also produced by a

slight binocular pressure upon the temporal part of the eyeballs, while forward movements occur when the eyes are forcibly opened wider than their normal condition, or when they are slightly pulled apart by a traction exerted on the temporal side of the lids.

Subject 2. Closure at this distance of the screen produced backward movements as in the case of subject 1, but of a less extent. The binocular movements were judged to be 4 to 6 inches in length.

Subject 3. In this case the lateral movements were similar in character to those of the first two subjects; the third dimensional component, however, differs radically. With monocular closure this component was detected for the left eye alone, and was then only markedly apparent when the vision of the right eye was intercepted. The component was not present at the zero point, but only for positions where lateral movements occurred; even here it is hardly accurate to speak of a third dimensional component, for the direction of the movement was a matter of interpretation. The movement was always seen either in a lateral or forward direction, but never as an angular resultant as in the other cases. Normally the movement would appear as lateral, yet it could be interpreted as forward, but never as backward. With binocular closure, the movements would be normally interpreted in a lateral direction, yet with some positions no forward interpretation was possible; occasionally they could be seen as a resultant moving in both a lateral and forward direction; in other positions they could be interpreted as either lateral or forward, but not as a resultant. Evidently the position of fixation is a determining factor. There was no reversal of direction for extreme convergence as with subject 1. Binocular pressure, and an outward traction on the eyelids produced forward movements.

Subject 4. The phenomenon did not occur for monocular closure. Binocularly, the component was forward and 1 to 2 inches in length. The movement was seen as a resultant, and

did not seem to be a matter of interpretation. In several cases the fixated object moved forward and to the left during a partial closure, *ab* (fig. 7). On opening the eyes the object at first moved straight backward, *bc*, and then slowly to the right and forward, *cd*, giving the impression of being nearer the subject than at the beginning. The object fixated was a small square of paper pinned to the screen. Sometimes the paper and the white lines would move forward while the cloth background would remain stationary; again the lines might move, but not the paper, or conversely. When the paper object was not used as a fixation point, either the lines would move forward or the cloth backward according to the direction of the attention. Evidently an interpretative factor is present.

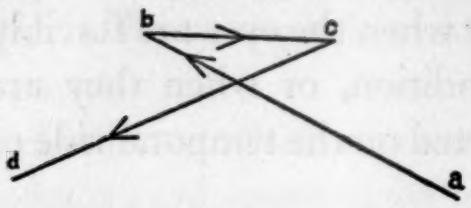


FIG. 7. Irregular image movements.

Subject 5. The movements occurred only for binocular closure but for all fixation positions. The direction was a matter of interpretation, being seen either as lateral or forward. The length of the forward movement was judged to be 2 to 3 inches. Forcible opening of the eyes produced no movement effects, though the paper object appeared to widen perceptibly in its vertical dimension. Traction on the lids caused a slight forward movement, the object becoming larger in both dimensions. The phenomenon was absent for subject 6 for all forms of stimulation.

This phenomenon was noticed by subject 1 during the first part of the experimentation. After being once observed, the phenomenon was thereafter very striking, and could not be overlooked. None of the other subjects noticed the movement until their attention was directed to its detection. After the suggestion, some subjects detected the movement at once, while others did so with difficulty. Only the possible presence and not the direction of the movement was suggested to the subject. After once perceiving this movement in a certain di-

rection, these subjects could not reverse the direction by any effort of interpretative attention. Another subject (C. H. B.) was afterwards used who succeeded in reversing these movements in direction. At first he was asked to study these image movements carefully, reporting all peculiarities which he was able to detect. The third dimensional component was not noted. The possible presence of this movement was then suggested, but after careful scrutiny it was not detected. The subject was then asked to interpret the movement in a third dimensional direction if possible. After some trial, backward movements were seen, and later he succeeded in producing forward movements also. Finally he was able to change the movements at will from one direction to the other, although the backward movement was the longer and much easier to produce. It generally took two to three trials to change from the forward to the backward direction, but six to seven for the contrary change. This control of direction was obtained for both monocular and binocular closure. With this subject the movement was seen as an angular resultant of the two directional components; the image moved both laterally and in a third dimensional direction. The mental effort in this control was described as an ideational expectation of the desired direction with a general sense of strain about the eyes; no differences in the nature of this accompanying strain could be detected for the two directional results secured. After several days' trial, the movement would normally be directed backward unless prevented by mental effort. The image always decreased in size and brightness for both monocular and binocular conditions and for both forward and backward directions of movement, though these effects were greater for the backward direction.

It is evident that this phenomenon varies so markedly with different subjects that no general statements applicable to all individuals can be made. Only a few characteristics can be summarized: Interpretation, or a central condition, is evidently

a considerable factor whose importance varies with individuals. The presence and direction of the movements are thus partly determined in several cases. However, there are certain given conditions whose determining influence the interpretative factor cannot overcome. The strength of these varies with individuals. For instance, the direction of the movement cannot be reversed except in the one case, and even here the backward movement is the longer and the easier to produce. The binocular factor is one of these determining conditions, for the presence of the movement occurs only with binocular closure in some cases, and its extent is generally greater than with monocular closure. The extent and direction of the movement also vary with the degree of convergence. The position of the eye in the socket is evidently of no slight importance. The character and direction of the causal force change the direction of the movement. Also changes in the image or the eye itself are conditioning factors, for the phenomenon is present in the first two subjects for monocular closure at the zero points, where, as we shall see later, there are no eye movements, nor a retinal shifting of the stimulation. However, the causes of these third dimensional movements will be discussed later.

XII. Corresponding Eye Changes.

1. *Historical.*

We have now to investigate the corresponding eye changes, *i. e.*, the physiological phenomena which accompany or condition, as the case may be, the various psychological phenomena previously described. The attempt will then be made to systematize and explain as far as possible these optical experiences in the light of their physical conditions with the hope of gaining some insight into the problems of space perception.

To state the psychical phenomena in physiological terms, three possibilities are open, (1) alterations in the form of the eyeball, *i. e.*, some disturbance in the refractive media, (2) some

displacement of the eyeball in the socket and (3) normal rotary movements of the eye. These three will be termed for the sake of convenience the refractive, the displacement, and the rotation hypotheses respectively.

In considering these hypotheses, two aspects are involved: First, which of these changes is most likely to occur with pressure and closure, and, second, assuming its occurrence, which will best explain the observed facts. A consideration of the first question necessitates some statement of current opinions.

Variations in the curvature of the lens are the only refractive changes which current opinion is disposed to admit in ordinary experience. The form of the eyeball, the corneal curvature, and the relation of the optic axis to the fovea, are supposed to be constant. Formerly, various processes, such as changes in corneal convexity, alterations in the form of the globe, displacement movements of the lens, etc., were assumed to account for the accommodatory process, but accurate experiments have generally shown such assumptions to be unfounded.[1] In all these cases, however, the changes are supposed to be symmetrical to the normal position of the optic axis so that the stimulation is not shifted over the retina. Any disturbance which will account for these lateral image movements must be conceived as a shifting of the optic axis in relation to the fovea, or, in other words, the nodal point must be laterally displaced within the bulb. In this way the stimulation from an objective point would be shifted over the retina. Le Conte [2] assumes a slight torsional twisting of the globe to explain certain visual phenomena. However, the assumption is not directly supported by any observations. Tscherning,[3] Hess,[4] and Heine [5] have demonstrated a

[1] Helmholtz, Handbuch der Physiologischen Optik, 2te. Auflage, pp. 150–6.
[2] Le Conte, Sight, 185.
[3] Tscherning, Archives de physiologie, 158, 1892.
[4] Hess, Arch. f. Ophth. xliii, 477–542, 1897.
[5] Heine, *ibid.* xliv, (2) 299, 1897; Landois, Textbook of Human Physiology, p. 835.

lateral displacement of the lens during accommodation. Hess and Heine show that this movement is due to the weight of the lens, the direction always being downward, although the head may be in any position. Their measurements by different methods agree fairly well, giving a movement of .3–.35 mm. Under some conditions the amount was as high as .5 mm. It would seem that such a change would have some effect upon the position of the nodal point.

So far as is known to the writer, no such changes due to closure or finger pressure have been observed, but *a priori* they would seem to be possible. The eyeball is under pressure from the surrounding tissues, the eye muscles and the intra-ocular tension. This latter is so great that it very largely determines the shape of the globe, its tendency being to force the eye-ball to approximate the spherical form. With death this pressure decreases and the globe alters form so that measurements taken after death are unreliable. The weakest part of the wall is apparently the juncture of the sclerotic and the cornea, for an increased intra-ocular pressure after death bulges the bulb out at this place, and hence decreases the corneal convexity. The eye muscles are attached to the globe near this position, and it is possible that their continuous tension may account for the short antero-posterior axis.[1] The intra-ocular pressure is known to vary from time to time.[2] The lens capsule approaches the wall of the bulb a short distance back of this juncture of the cornea and the sclerotic, and the finger pressure is also applied near this place. If any slight changes are possible at all, it would seem that a vigorous finger pressure should produce some effect upon both the cornea and lens. Such an assumption is extremely hypothetical; it is merely desired to call attention to the *a priori* possibility.

As to the second hypothesis, forward and backward displacements of the bulb within the socket due to lid closure, forcible

[1] Helmholtz, *op. cit.* 6–8.

[2] Hermann, Handbuch der Physiologie, iii, 1, 32–35.

opening of the lids, external mechanical pressure, and varying internal pressure are admitted by physiological authorities.[1] Müller[2] first noticed the forward displacement due to the forcible opening of the lids beyond their normal condition, and the observation was afterward confirmed by Donders[3] and Berlin.[4] Donders also detected a backward displacement with eye closure. The total amount of this forward and backward displacement is from .75 to 1.5 mm., the amount apparently varying according to the position of the fixation in the field of regard. Berlin also maintains such a displacement in normal rotation, but in this case the movement was not directly observed, but inferred from his determinations on the position of the center of rotation. This inference is not generally accepted, however.

As to any lateral displacement, *i. e.*, any movement of the bulb in a right and left, or up and down direction, the consensus of authoritative opinion maintains a negative attitude, at least for normal conditions.[5] This involves the question as to the fixity of the center of rotation which has been the subject of much experimentation and discussion. Berlin in the paper cited is the strongest advocate of a lateral displacement in normal rotation. Again he assumes such a movement in order to explain certain phenomena, but, as Hering points out, the facts can be as well explained by another assumption. An excellent review of the literature on this point is given by Hering,[6] in Hermann's Handbuch.

Berlin also maintains a lateral displacement in closure and forcible opening. According to him the amount and direction

[1] Helmholtz, *op. cit.* 614; Foster, Textbook of Physiology, iv, 134; Bowditch, American Textbook of Physiology, ii, 299; Hermann, *op. cit.* III–1, 453; Landois, *op. cit.* p. 866.

[2] Müller, Archiv. f. Ophth. xiv, 3. S. 183.

[3] Donders, Archiv. f. Ophth. xvii, 1. S. 99.

[4] Berlin, Archiv. f. Ophth. xvii, 2. S. 154.

[5] Helmholtz, *op. cit.* 614; Foster, *op. cit.* 134; Bowditch, *op. cit.* 299.

[6] Hermann, *op. cit.* III–1, 452–468.

of these movements vary according to the position of the fixation in the field of regard. His determinations gave values as high as .689 mm. In these tests, the movements are again inferred on the same grounds as formerly.

So far as the writer knows, no author has mentioned a lateral displacement due to finger pressure. On dissection the eyeball is found to be firmly imbedded in the surrounding masses of tissue so that any perceptible lateral displacement is practically impossible. However, it must be remembered that these tissues assume a rigidity in death not at all comparable to their elasticity during life.

As to the third hypothesis, the only question is whether or not closure and pressure will actually produce rotation. The lids and the eyeball are anatomically connected, the lining membrane of the lids being continuous with the conjunctiva of the cornea, but it is extremely doubtful if this connection is close and rigid enough to transmit movement. A functional connection also exists, certain of the lid and eye muscles being innervated by the same nerve. However, any definite and necessary correlation of movements is denied. In a condition of extreme convergence, lid closure produces a slight rotation for the writer, for it is impossible to maintain a high degree of convergence during continuous winking or a closure of three to five seconds. On opening the eyes, the fixated object is always found to be doubled heteronymously, *i. e.*, the eyes have been forced to a more divergent position. This occurs with both monocular and binocular closure, but the binocular effect is the greater. This may be explained on the hypothesis that the eyes are maintained in a highly convergent position only by the aid of the foveal stimulation from the object in the reflex attempt to maintain unity of vision. On intercepting this stimulus by closure the eyes tend to spring back to a more normal position. This doubling of the fixated object has been noted when vision is intercepted by other means than closure.[1] Neverthe-

[1] Angier, Zeitschrift f. Psych. u. Phys. d. Sinnesorgane, (37,) p. 239, 1904.

less, this phenomenon was not detected in the other subjects tested.

Nearly all authorities assume that finger pressure produces a rotation. This assumption arises in connection with the image movements due to external pressure which have been commented upon by almost all writers on vision. Perceiving that the eye does really move, and being indisposed to admit any other form of movement, rotation is invoked to explain the visual phenomena. Attention is directed to the fact that this is a mere assumption, no positive evidence, so far as known to the writer, being given in support of the proposition. James,[1] Le Conte,[2] and Hering[3] make no definite statements, though rotation seems to be implied. Helmholtz, Stewart, McKendrick and Snodgrass and Mach make explicit statements,[4] although they give no evidence that the eye actually rotates in these conditions; rotation seems to be taken for granted.

Pierce[5] is the only writer the author has discovered who has mentioned image movements resulting from lid closure. He states that the movements are upward in his case, but attempts no explanation in eye terms.

To summarize: Image movements due to both pressure and closure have been noted. No attempt has been made to explain those due to closure. The accepted explanation of the pressure movements is in terms of the rotation theory, but rotation is a mere assumption which may or may not be true. Forward and backward displacements of the bulb under closure and pressure are conceded as facts, but any lateral displacements under like conditions are generally denied. Changes in the refractive media asymmetrical to the normal position of the

[1] James, Principles of Psychology, ii, 234.

[2] Le Conte, *op. cit.* 107, 256.

[3] Hermann, *op. cit.* 535.

[4] Helmholtz, *op. cit.* 743–4; Stewart, Manual of Physiology, 805; McKendrick and Snodgrass, Physiology of the Senses, 174–5; Mach, Analysis of the Sensations, p. 59.

[5] Pierce, Space Perception, 310.

optic axis possibly may occur in convergence. So far as known to the contrary, such changes may also result from pressure or closure, though authorities would probably maintain a sceptical attitude. In other words, one theory is as valid as another as regards the possibility of the assumed changes.

2. *Rotary-Displacement Movements of the Eye.*

Whatever the eye changes may be conditioning these visual phenomena, it is evident that they are produced by pressure, closure, and suction, that their character and amount is conditioned by the direction and intensity of the producing force, the position of the eye in the socket, and the degree of convergence. A moment's inspection also reveals the fact that the eyeball does actually move during pressure and closure, but several considerations lead one to suspect that this movement is not a normal rotation: (1) As noted, this movement of the bulb due to pressure, closure, or suction feels to the subject distinctly different from a normal rotation or a "superimposed rotation." The movement also appears different to an observer. One can easily notice this difference when attention is directed to the comparison. With pressure, the bulb appears to be rotated about a center in the back part of the head, while in normal rotations the center appears to be within the globe. Again, if one exerts a pressure and then voluntarily rotates the eye while maintaining the pressure, this "superimposed rotation" appears distinctly different from the pressure movement. The observer can immediately tell when the voluntary rotation begins. If the subject fixates the eye of the observer, the latter is under the impression that the subject's fixation does not change during pressure or closure, but does so during a superimposed rotation. This is true even when the observer does not see the subject's eye which is not manipulated. (2) It is extremely difficult to conceive either how or why mere suction should produce normal rotations. If a decrease of air pressure produces rotations, then the normal atmospheric pressure must be an

efficient factor in conditioning normal eye movements. While pressure might produce a rotation, yet it is difficult to conceive why the extent and direction of this rotation due to either pressure or suction should be so conditioned upon the mere position of the eye in the socket. (3) According to the rotation hypothesis, the eye must rotate in a direction opposite to that of the image movement, if the inverse relationship between the retina and the visual field is true. Thus in subject 1, the eye must always be rotated back toward the zero point, for the image moves in a peripheral direction. Consequently for a fixation position in the upper part of the field, a nasalward pressure must cause the eye to rotate downward, this rotation conditioning the upward movement of the visual field. However, if one now maintains the pressure and voluntarily rotates the eye further toward the center of the screen, this additional rotation will produce, not an additional upward displacement, but a movement in the same direction as that of the rotation. This statement is also true for suction.

The following series of experiments were designed (1) to determine the nature of these bulbular movements and (2) to determine whether they conditioned the image displacements, for it is possible that eye movements might occur and still have nothing to do with the observed visual phenomena. In fact, as we shall see, this sometimes does occur. The results of each test will first be stated, followed by a description of the method used.

1. The stimulation from external objects is actually shifted over the retina.

This is clearly seen from a test involving the blind spot. One eye is closed, and the fixation is arranged until the object falls just within the "blind area," and is consequently invisible. Winking and pressure immediately bring it into distinct view, the apparent fixation meanwhile remaining constant.

FIG. 8. Distortion of pupil by pressure.

2. Corneal movements may occur with both pressure and

winking, but there is no fixed relation between their occurrence, direction, or amount, and the presence, direction, or amount of the concomitant movements of the visual field. Image movements may be present with no corneal movements, and corneal movements may occur with no image movements. The visual field may move in any direction, while the cornea meanwhile may move in only one direction.

With closure the cornea always moved nasalward, so far as observed.

With light pressure, the cornea always moves in the same direction as the pressure; hence a nasalward pressure will produce the same direction of corneal movement as does winking. As formerly noted, the direction of the image movements in the two cases are identical with subject 1.

With strong pressure, the cornea at first moves in the same direction as the pressure, but then may stop and move backward toward its original position. The amount of this return movement depends upon the position of the eye in the socket and the strength of the pressure. The return movement may be even larger than the original movement, so that the cornea has finally been displaced in a direction opposite to that of the pressure. For instance, a nasalward pressure, when the eye fixates an object in the temporal part of the field of regard, gives a nasalward corneal movement with no return. As the fixation is changed more and more to the nasal part of the field of regard, larger and larger return movements occur, until in the extreme nasal fixation positions, the cornea finally returns to a position temporal to its starting point.

The amount of this movement varies with individuals, but may be as high as 3 mm. Its presence and amount can be voluntarily controlled to some extent by altering the character of the pressure.

A series of tests was made for all fixation positions on several subjects and by different observers. Two methods were used; shadows of small stationary objects were thrown on the white

sclerotic at its juncture with the cornea, so that the edges of the shadow and the colored iris would just touch each other. If the cornea moved, the shadow and the iris would separate, and the amount of white sclerotic seen between them would indicate the amount of movement. The observer also sighted monocularly at the outside edge of the iris, through a series of small parallel threads tightly stretched on a frame. This frame was firmly fixed close in front of the eye experimented upon. The subject's head was placed in the mouth-bit head-rest. The movements were large enough to admit of certainty as to direction.

These results are conclusive as against the rotation hypothesis; for, if the movements were normal rotations, the cornea should move in a direction opposite to that of the image movements, and there should be some constant relation between the two series as to extent of movement. Furthermore, it would be impossible to have an image movement of 5 degrees with no corresponding corneal movement, nor a corneal movement of 2 mm. with no image movement. Such cases frequently occurred with subject 1.

3. Apparent retinal movements can be observed through the ophthalmoscope. These retinal movements bear certain constant relationships to the movements of the visual field. The two series always occur together; when one is absent, the other is also absent. They are simultaneous, beginning and ending at the same time. They always have the same direction. Their lengths differ in absolute amount, though the ratio between them approximates a constant. The apparent retinal movement is thus a small-sized duplicate of the image movement, and the charts representing the image movements for the different fixation positions on the screen will also represent the directions and relative lengths of the corresponding retinal movements for the same fixation positions.

These retinal movements have been called "apparent" because their interpretation is ambiguous. If refractive disturb-

ances occurred according to the first hypothesis, the line of sight of the ophthalmoscopic observer would be shifted over the retina and an apparent retinal movement would be perceived. The test is not decisive as regards the first and second hypotheses.

The experiment corroborates the test involving the blind spot. The stimulation from objects is actually shifted over the retina. Furthermore, no central factors can be adduced to explain the lateral image movements, for the direction and extent of the image movement stand in a fixed relation to the direction and extent of this retinal displacement of the stimulation.

These results combined with those on the corneal movements indicate a lack of fixity between those two series of movements as to presence, direction, and extent. This is a further conclusive proof that the eyeball does not undergo a normal rotation. For if these apparent retinal movements were due to a normal rotation of the eye, it is evident that there should be some constant relation between the two series. It would be impossible to have a large corneal movement with no corresponding retinal movement, and *vice versa*.

These conclusions are based upon a long series of tests made on different subjects and by different observers. The different observations were in perfect agreement. The instrument used is based upon the indirect method giving a magnified and inverted image of the retina. A frame over which was tightly stretched a system of fine vertical and horizontal threads 3 mm. apart was fastened to the instrument so that the ophthalmoscopic field of view was seen through this non-magnified system of lines. Knowing that the cornea and pupil moved nasalward, the line of sight of the instrument was directed just within the nasal side of the pupillary aperture. Thus only considerable movements of the bulb would intercept the ophthalmoscopic view of the retina, and since the instrument magnifies from 10–12 times, the perceived retinal movements may be quite large. By selecting some well-defined and distinct point on the

retina, the direction of the movement can be easily noted. Any accurate measurement of the lengths of the movements is difficult without a quite extended preliminary practice, and even then the results are perhaps crude. Discrepancies were eliminated by taking the average of a large series of measurements.

If one chooses a position on the retina anywhere near the fovea, the instrument will intercept this eye's vision of the fixated object, so that any simultaneous comparison of the retinal and image movements is impossible. However, such a position has the advantage of offering a much more distinct and well-defined spot for observation. Both methods were used in a comparison of direction. The head was in the primary position before the screen, so that the direction of the image movements for all fixation positions was known from the preceding determinations. The retinal movements for the same fixation positions were then noted for pressure and partial closure, and the comparison between the two series made. A peripheral spot on the retina was selected, and a simultaneous comparison of the directions of the two movements was also made. Since the instrument gives an inverted image, all perceived movements must be reversed in direction. The observations were made on three subjects by two observers with conclusive results.

A comparison of the two series as to length necessitates a simultaneous measurement of the two movements. The subject produces an image movement of 5 cm. on the screen, and the observer measures the corresponding retinal movement. Then 10, 15, and 20 cm. image displacements are produced, and the retinal movements likewise measured. The performance is repeated a sufficient number of times to give a reliable average. The various results corresponding to the four degrees of displacement are averaged. Since the image displacements bear to each other the ratios of 1:2:3:4, it is evident that these four average results should approximate the same ratios, provided there is any constant relation between the two series. To obtain any reliable outcome several precautions must be taken: In

any set of results to be averaged and compared, the same point on the retina, and the same direction of image movements must be used throughout, for the length of retinal movement corresponding to a 10 cm. image displacement will vary markedly according to (1) the position of the observed spot on the retina, (2) the direction of the movement, and (3) with different individuals. These controlling factors were empirically detected, and need not be further discussed here. The results of several careful series of measurements are given in Table VIII. Since both the direction and the extent of the image displacements must be as accurately controlled as possible, finger pressure alone was used to produce the movements. Even then it is somewhat difficult to maintain a desired image displacement long enough to be accurately measured. As a control, a series of measurements was taken where the eye was voluntarily rotated for 5, 10, 15, and 20 cm. It is much easier to control the position of the eye in this manner than by pressure. However, in this case the ratios do not approximate the ideal much more closely. The variations from the norm may easily be due to the difficulties of measurement and of exact control of the image displacements.

TABLE VIII. RATIOS BETWEEN VISUAL MOVEMENTS AND CORRESPONDING RETINAL MOVEMENTS.

Subject	6	1	1	1
Number of measurements	40	40	75	50
Cause of movements	Pressure	Pressure	Pressure	Rotation
Direction of movements	Up	Up	Temporalward	Up
Ratios of image movements	1:2:3:4	1:2:3:4	1:2:3	1:2:3:4:5
Ratios of Retinal movements	1:2:2.7:3.4	1:1.7:2.6:4	1:2:2.96	1:2:2.8:4:5.5

4. The apparent fixation as felt by the subject remains stationary with both pressure and closure, but yet moves with every superimposed rotation. This is true no matter whether the opposite eye is open, closed, or has its vision intercepted.

5. A negative after-image affecting any part of the retina does not move with pressure or closure, but does move with a superimposed rotation. A foveal negative after-image is always located at the fixation point, and moves with it.

The non-movement of negative after-images under pressure has long been noted and frequently commented upon in the literature. A long series of observations for all eye positions, for all degrees of pressure, and with all conceivable variations of method have confirmed the statement. The images are perfectly stationary during pressure, but immediately move when the apparent fixation is changed by a superimposed rotation. If an image is developed while the visual field is displaced by pressure, the same statement is true; on releasing the pressure, the displaced visual image moves back to its original position, leaving behind in its place a stationary negative after-image. In these tests care must be taken to develop only a monocular after-image, as binocular images do not separate or become double. Hence the non-movement of the images in this case might be due to the stationary opposite eye.

6. The same statement holds for the blood vessel shadows, all entoptic phenomena, and for the image of any object affixed to the eyeball. They are stationary for pressure or partial closure, but move with every superimposed rotation.

These results are conclusive against the refractive hypothesis, for, according to this theory, the rays of light are increasingly deflected from their normal course as they pass from the cornea to the retina. Consequently, the shadows of any entoptic particles situated in the anterior part of the globe must be shifted on the retina to an extent proportional to the distance of the particles from the retina. Entoptic phenomena having their seat on the retina would not move at all, while those having a corneal location should move to the same extent as the image of an external object; those due to particles located between the retina and the cornea should undergo a movement proportional to the distance of the particles from the retina.

Such a phenomenon as just described was obtained by one test. The usual device of a black cardboard with a small needle hole was used to bring out the entoptic phenomena due to particles located in the anterior part of the globe. Three entoptic objects were seen in the visual field in the order of 1, 2, and 3 from left to right. With pressure these objects all moved and assumed the inverse positions of 3, 2, and 1. Object 1 had moved more than 2 or 3, and 2 more than 3. This seemed at first a conclusive proof of the refractive hypothesis. However, the same result was obtained by keeping the eye still, and slightly moving the cardboard sidewise. In this case the direction of the pencil of rays entering the eye from the pinhole has been changed. Since the pupil generally moves with pressure, we have the same conditions, a relative movement of the pupil and the pinhole, which is sufficient to account for the observed result. The test was utterly valueless for the purpose in hand.

However, under all ordinary conditions no movement of these entoptic objects has been detected. The observations were carried on for a considerable time at opportune moments. With practice one can become quite sensitive to these phenomena. For the writer, many came out quite distinctly when looking at freshly fallen snow reflecting bright sunlight. But we have the possibility that all the objects seen under ordinary conditions have a location on or near the retina, and, of course, the non-movement of such objects would be no proof against the refractive hypothesis.

As a decisive test, the attempt was made to fasten some object to the cornea so as to be visible. Strips of black paper were laid on the cornea over the pupil, but the image obtained was so blurred and confused in outline that judgments were unreliable. The object was then affixed to a plaster cast by wires so as to be held some distance before the pupil. The cast firmly adheres to the cornea, and consequently the object is stationary in respect to the perceiving eye. The object used must be small and light, rigidly attached to the cast, and as near the eye as possible

without sacrifice of distinctness of outline. With the disturbances of accommodation by cocaine, and the discomfort arising from the lid-holders, etc., distinctness of vision is absolutely necessary to insure reliability of judgments. Hence foveal vision is indispensable, and it is extremely difficult to attach the cast to the cornea so that the object will be foveally perceived. After a long series of exasperating failures, the following device was hit upon: The object used was a piece of black cardboard of light weight 2.5 cm. in diameter. This was pierced full of pinholes 3–4 mm. apart, and attached to the cast by two fine copper wires 4 cm. long. The apparatus was quite rigid. With these dimensions it was relatively easy so to attach the cast to the cornea that some part of the cardboard would be foveally perceived. An incandescent lamp in the opposite side of the room was used as a fixation object. The light coming through the pinholes rendered the lamp and the squares of cardboard between the pinholes sufficiently distinct for confident judgments. Two successful tests were made on the right eye of subject 1, for different directions of pressure, and for different positions of the eye in the socket. Obviously closure could not be used as a stimulus. The results were so striking and conclusive that it was not deemed necessary to repeat the test on other subjects. The image of the light belonging to the right eye would move from 20–25 cm. (3–4 degrees), but the paper object remained practically stationary with the left eye's image of the light, moving, however, with every superimposed rotation. As a matter of fact, the paper object did move slightly (1–2 cm.), but in a direction opposite to that of the visual field. This slight movement in the opposite direction will be considered later. This may be due to refractive changes, but if so, these changes tend to oppose, and not to produce the movements of the visual field. For the present we will ignore these slight movements, and regard the object as remaining stationary.

As an evidence of the sincerity of these observations, it may be well to state that the writer had become convinced of the

truth of the refractive hypothesis, and fully expected to perceive a movement of the object corresponding to that of the electric light.

Two former experiments have proven that the stimulation from the external object is actually shifted over the retina, and that the direction and extent of this shifting conditions the direction and the length of the perceived image movements. This retinal shifting can occur only by a movement of the external object, a refractive change, or by a movement of the retina. Some form of eye-movement must occur.

7. The behavior of the Purkinje-Sanson images under pressure and closure throws additional light on these bulbular movements.

The corneal image moves in relation to a fixed point on the bulb, *e. g.*, the outside circumference of the iris, in the same direction as that of the perceived visual image. In relation to the corneal image, the anterior lens image moves in the same direction as the visual field, while the posterior lens image moves in a direction opposite to that of the visual field.

These results are derived from several observations. The movement of the anterior lens image in relation to the corneal image was noticed by three observers on five subjects. Four persons observed the movement of the posterior image in relation to the corneal image on two subjects. All observations were in agreement. The movements are large enough to admit of certainty as to direction.

The significance of these observations depends upon the well-known fact that changes in the relative positions of these reflected images indicate corresponding changes in the relative positions of the three centers of curvature of the corresponding reflecting surfaces. Hence the above statements in regard to the images apply equally well to four known and fixed points in the globe, a point on the anterior surface of the cornea, and three points on the optic axis at differing distances from the cornea. In other words, they indicate the existence and direction of a

deflection in the position of the optic axis in relation to the direction of the resulting movements of the visual field. The proposition may easily be demonstrated by observing the images during a normal rotation.

Consequently we may affirm that with pressure and closure, the optic axis is deflected from its original position in a direction opposite to the resulting movement of the visual field. Hence the stimulation from the fixated object is shifted from the fovea over the retina in a direction opposite to that of the visual movement. This inverse relation between the directions of the retinal shifting of the stimulation and the corresponding image movement agrees with the well-known facts as to the spatial reference of the retina. These results also agree with the empirical facts regarding the direction of the retinal movements perceived through the ophthalmoscope. If the stimulation is shifted from a point on the retina to the left, the retina moves to the right, or in the opposite direction. Hence the retina must move in the same direction as the visual image, a relationship empirically established.

We are now in a position to state the nature of these eye movements. Only a few general statements are applicable to all cases. The more detailed descriptions will apply only to typical situations with a given individual.

1. Whenever corneal movements occur with no movements of the visual field, the eye undergoes a pure lateral displacement within the socket, *i. e.*, a movement wherein there has been no deflection in the position of the optic axis. The optic axis is still parallel to its original position. The amount and direction of this displacement is indicated by the extent and direction of the observed corneal movements. The possible amount varies with individuals, but may be as high as 2–3 mm. with strong pressures.

In such a displacement it is evident that no visual movements could occur because the relative positions of the fovea and nodal point have not changed in reference to the fixated object. The

stimulation would still remain on the fovea. The same statement applies to the ophthalmoscopic line of sight. There can be no shifting over the retina unless the nodal point and the retina change their relative positions toward external objects, *i. e.*, a deflection in the directional position of the optic axis.

This pure displacement generally occurs at the zero points, though the amount is quite small. It occurs quite frequently with some individuals when pressure is used. Subject 6 often found difficulty in obtaining any image movements with pressure, though marked corneal movements were easily observable. If the pressure were maintained for 10–15 seconds, the visual field would then begin to move, although the cornea meanwhile remained stationary in its displaced position. Ophthalmoscopic observations demonstrated that no retinal movements occurred during the corneal movement, but were present during the succeeding image movements. Subject 1 succeeded in controlling these displacements with pressure. The image movements could be entirely repressed or initiated at any time during the continuous pressure. Retinal movements would occur only simultaneously with the image movements. Often the eye would be displaced to such an extent that the iris would intercept the ophthalmoscopic line of sight, and yet no retinal movements could be perceived.

2. Whenever image movements occur, the bulb undergoes both a displacement within the socket and a rotation. This movement may be conceived as a rotation of the bulb about some center other than the normal one. In some cases it is possible that the rotation may be a normal rotation, but this is not always so, and probably not generally true.

This statement expresses the facts that the movement cannot always be a normal rotation, and that there can be no image movement without a deflection of the optic axis from its original directional position.

3. The position of this center of rotation is extremely variable. It may be different in two cases where the image movements

are identical. Different image movements may be caused by eye movements where the centers of rotation are identical. During the course of any image movement, the center of rotation cannot always be conceived as stationary, but as constantly shifting, *i. e.*, the eyeball does not necessarily rotate about a fixed center, but rather changes its position in an irregular manner. At any particular time in the course of the movement, the eye may be conceived to have attained that position by a rotation about some center. The center of rotation is thus but a conceptual position useful to describe the position of the eye at any particular time. However, in some cases, the center may be stationary, the eye actually rotating about it. Such a case would occur whenever the cornea remains stationary during the course of the movement; the center of rotation must be located on the surface of the cornea.

This center of rotation in any particular case may be roughly determined from the image and corneal movements. One can compute the retinal correspondent of the image movement, *i. e.*, the relative movement of the fovea and the nodal point. Knowing the corneal movement and the difference between the movements of the fovea and the nodal point, the position of the center of rotation, *i. e.*, the point of intersection of the two positions of the optic axis or its prolongation, is easily determined.

Consequently, the image movement remaining constant, any change in the amount of the corneal movement must be conceived as a change in the position of the center of rotation; the same is also true if the corneal movement is constant and the image movement varies in length. As formerly noted, the length of the corneal movement has no constant relation to the length of the image movement. The relation is extremely variable even in normal conditions. By slightly altering the character of the pressure one can entirely suppress either the corneal movements or the image movements. This variability means a change in the position of this conceptual center of rotation. In the case of a nasalward fixation with subject 1, the image and corneal

movements are both nasalward. The fovea must thus move nasalward more than the cornea. Hence the center of rotation is some distance in front of the cornea. As one continues the pressure the cornea gradually moves backward, finally reaching its original position. In other words, the center of rotation has gradually moved nearer the eye, being finally located at the cornea. A further pressure causes the cornea to move temporalward of its original position, the center of rotation then being within the globe.

4. The following description applies to those having zero points: With nasalward fixations the center is located somewhere in front of the retina; with temporalward fixations it is located back of the cornea. In either case it may be either within or without the bulb, but generally at some distance outside. Some observations in the test with the plaster cast directly confirm this interpretation. A wire, 10–12 cm. in length, was attached to the cast and the assistant observed its movements during pressure. In temporal positions the end of the wire moved much more than the cornea, and in the same direction. It gave the impression that the center of rotation was in the back part of the head. In a nasalward position the end of the wire appeared to move slightly in a direction opposite to that of the cornea. The center of rotation appeared to be at some point on the wire.

With fixation positions in the upper and lower part of the field of regard, the visual image moves up and down respectively while the cornea moves nasalward. Here two separate eye movements must occur, — a pure nasalward displacement indicated by the corneal movement, and an upward or downward rotation about a center located in the cornea. If the fovea did not move nasalward to the same extent as the cornea, the resulting image movement could not be exactly vertical in direction. Again, if the center of the rotary component were not located at the cornea, the corneal movement could not be exactly horizontal; it must necessarily have some vertical component. Hence in these cases we must conceive the eye to undergo two distinct

movements, a pure displacement and a rotation about a fixed center wherein the fovea moves in the same direction as the image movement.

In the former cases of temporal or nasal fixations we likewise had two components in the movement, — a pure displacement, and a rotation. We described the total movement as a rotation about a conceivable center. As to the actual center of the rotary component, nothing was said. This might be at the normal center of rotation, or elsewhere, or occupy a variable position. One has no ground for any positive assertions. In the case of vertical image movements, we have these two components separate and distinct, a nasalward displacement and a rotation about a center in the cornea. It is possible that the same situation obtains in all cases, and that the rotary component is a rotation about a center situated in the corneal surface, the fovea rotating about this point in the same direction as the resulting image movement.

3. *Refractive Changes.*

It will be remembered that in experiment 6 the image of an object affixed to the cornea moved slightly in a direction opposite to that of the visual field. Hence the stimulation from this affixed object must have been slightly shifted over the retina. Either the object did move in relation to the eye or some refractive disturbance was present. The first supposition is hardly possible, for the direction of this supposed movement has no fixed relation to the direction of finger pressure, but has such a relation to the image, or eye movements which are largely determined in direction by the position of the eye in the head. The fact, I think, proves some sort of a refractive change equivalent to a lateral shifting of the nodal point; this is necessary to account for the movement of the stimulus over the retina. This refractive disturbance is such as will minimize and not increase the image displacements due to eye movements. The presence of refractive changes was evidenced by other observations: (1) In subject 1, slight lateral movements of the

iris as a whole were occasionally noted, and very often the form of the pupillary aperture was markedly altered, being caved in on one side as represented in fig. 8. These observations are only of indirect value; however, if the iris can be thus moved and distorted, lenticular changes are at least possible. (2) Various indications of lenticular changes were present in the phakoscopic observations. In this test a pair of images was used. In observing the lateral movements of the lens images in relation to the corneal images during pressure and partial closure, it was observed that the pair moved unequally in direction and extent. They also moved nearer or farther apart, and occasionally moved backward or forward as well as sidewise. The image would appear to change size and form, becoming slightly blurred. These changes were detected by several observers upon different subjects. Nevertheless, the observers were not confident of their judgments; they were strongly impressed that such phenomena did occur, but the changes were so slight as to admit of no certainty as to their character. If such phenomena are present, they mean not only a disturbance of lens curvature, but also an inequality of refractive change for different parts of the surface. According to some observers,[1] this latter phenomenon occurs in normal conditions; Dobrowolsky, E. Fick, Michel, *et al.*, maintain that one section of the ciliary muscle may contract independently of the other portions, thus producing a change of curvature only in some one meridian. This contention is disputed by Hess. (3) With the ophthalmoscopic tests, it was noted that the image of the retina often became slightly blurred and confused during pressure and partial closure, as though the focal adjustment were imperfect. This fact also argues in favor of some refractive disturbance. (4) In experiment 7 on the eye movements, it was noted that the movements of a corneal image in relation to a fixed point on the cornea were identical for the two cases where a normal movement of the point of fixation equalled an image displacement due to pressure. In observing

[1] Landois, *op. cit.* p. 835.

the movements of the lens images in relation to the corneal images in these two cases, several observers were occasionally under the impression that this equality of movement did not always obtain. If this be so, the axis of the lens must be deflected from its normal position in the eye during pressure and closure. Nevertheless no assurance of certainty was felt in these observations.

In conclusion, the evidence as a whole is sufficient to warrant the assumption that refractive changes of some sort do occur, though it hardly constitutes any positive proof of the contention, or gives any definite idea as to the nature of the assumed changes. It is to be regretted that the instruments at our disposal did not allow of a more thorough investigation along these lines.

XIII. Visual Phenomena due to Eye Movements.

We have seen that these lateral image movements are due to a shifting of the stimulation over the retina in a direction contrary to that of the image movement, and that this retinal shift was conditioned by a rotary-displacement movement of the bulb whose effects were slightly minimized by a refractive change. These eye movements are known to occur for closure and pressure. We have now to inquire why these eye movements vary in amount and direction according to the position of the eye in the socket, the degree of convergence, and the nature of the producing force. To the writer the only satisfactory answer is as follows: The eye is not a perfect sphere, the sagittal axis being the longest. Furthermore the center of rotation is considerably back of the geometrical center. Consequently in rotation, the front part of the globe is displaced within the socket, being pressed against the surrounding tissues. This pressure from the elastic walls of the socket will increase as the eye is rotated peripherally. The globe is thus subjected to a system of forces from the air, the muscles and the environing tissues, a system which must be different for every fixation position and

degree of convergence. Finger pressure or lid closure constitutes a new mechanical force which disturbs the existing equilibrium. The eye is thus moved in some determinate direction, the line of least resistance. This direction will depend upon the direction of the mechanical force and the nature of the disturbed equilibrium. Why these movements should have the particular directions they do for each subject must depend upon anatomical peculiarities of the globe and socket. The results show that the position of the eye in the socket is a much stronger determining factor with those subjects having zero points, and this conception is peculiarly applicable to those cases. The eye is pressed firmly against the side of the socket as it is rotated peripherally, and closure forces it back toward a central position; hence occur the peripheral movements of the visual field. For the same force, this movement will increase in length in proportion to the pressure of the resistant tissues, *i. e.*, with the degree of peripheral rotation.

In the suction experiment the presence of the cage did not allow of any tests to determine the nature of the eye changes. The visual phenomena were identical with those of pressure and closure, and, as was mentioned, closure produced no image movements when the air pressure was much reduced. These facts are good evidence in favor of the assumption that the eye changes are also similar to those of closure. Moreover, such characteristic movements would naturally result from the above hypothesis. Suction would act upon the surrounding fatty tissues at their least resistant parts, and the eye would consequently be forced in that direction, or back toward a central position within the socket.

During normal rotations to extreme peripheral positions, this resistant force of the fatty tissues would finally become so great as to overcome the strength of the contracting group of muscles, and the eye would become distorted in position, being unable to move as far as attempted. It would be as if the eye were forced from this attempted fixation position back toward a

more central position. Consequently peripheral image movements must result. The case is exactly comparable to Mach's putty experiment. In these normal displacements negative after-images behave as in pressure and closure; this supports the assumption that similar eye changes occur.

As to the curved image movements and the sagittal rotations of the field, the ophthalmoscopic tests showed that these phenomena were conditioned by similar movements of the retina.

During a superimposed rotation, the visual field moves slightly in the same direction as the rotation for all those subjects having zero points. This phenomenon is a logical consequence of the empirical fact that with a constant pressure the direction and extent of the displacement are functions respectively of the direction and distance of the fixation position from the zero point. Suppose that one changes the fixation from *A* to *B* by a superimposed rotation, the pressure meanwhile remaining practically constant. The displacement now obtained is identical with that which would occur by first fixating *B* and then exerting the pressure. With fixation to the right, the displacement is to the right, and with fixation above the zero point, the displacement is upward. Consequently, if one changes the fixation from a point above to a point to the right of the zero point by a superimposed rotation, the visual field must move down and to the right, a direction identical with that of the rotation.

XIV. Visual Phenomena due to Refractive Changes.

Under this heading must be grouped the inequalities of displacement for different parts of the visual field and the changes in size, form, and brightness of the images. In fact these phenomena can hardly be explained in any other manner, and may rather be regarded as additional evidence in favor of the occurrence of refractive changes. The decrease in brightness and the blurring and confusion of surface and contour are signs *par excellence* of a disturbance in focal adjustment. The alterations

of form and size of the monocular images may be due to three causes: (1) they may be due to the inequalities of displacement. This is not a complete explanation, for such changes also occur at the zero points where no displacements are present. (2) The changes in size may be due to the third dimensional movements; a backward movement would tend to make the image appear smaller. This again is not the sole explanation, because the image decreases in size for both directions of movement. That these movements are one determining factor may be seen in the case of voluntary control of the direction; the apparent decrease of size is much greater for the backward direction. (3) There must be a third factor constant for all subjects. This, I take it, is the confusion of outline. The edge of the image becomes frayed and ragged, and the area of relatively intense stimulation is decreased. This gives the impression of an actual shrinking of the boundary lines. This effect may be unequal on the various sides, and hence the image sometimes appears to be altered in form. These changes in size and form are complicated in binocular closure by a fourth factor — the doubling of the images.

The inequalities of displacement cannot be explained by the eye movements because the eye can be voluntarily rotated so that it will have the same position in reference to the external objects as it had in a given pressure movement. The only difference in the positions of the eye in the two cases is in relation to the socket. The optic axis in each case is directed toward the object whose image is fixated, but yet peripheral objects do not stimulate the same parts of the retina in the two conditions. Hence some refractive disturbance must occur. The eye movement might explain part of these peculiarities because the stimulation is shifted on the retina, and as is well known, the space value of the retina varies. For instance, the distance *HX* (20 cm.) in fig. 5 would tend to become longer after the displacement because the stimulation has been shifted nearer the fovea. The same is true of the distance *XE*. The distance *EB*, on the

contrary, should become shorter for this reason, while as a matter of fact it has been lengthened 2.5 cm. Hence some factor must here operate not only to account for this 2.5 cm., but also to overcome the normal shortening due to the increased peripheral location.

This phenomenon would result from such a movement of the lens as described under (4) in the section on refractive changes. This may be demonstrated in an eye model by rotating the lens about its vertical axis. This result is due to the fact that the lens curvature is not uniform, and hence the refractive index varies for different portions.

XV. A Statement of a Class of Visual Illusions of Motion in Terms of Muscular Innervation.

We have remaining from the experiments on the eye movements a group of significant facts which still demand some explanation: the point of fixation, negative after-images, entoptic phenomena, and the object affixed to the eyeball did not move with pressure or closure, but did move with every normal or superimposed rotation. In other words, the stimulation was stationary on the retina, and the corresponding images were stationary with certain eye movements, but moved with others.

Helmholtz [1] noted the non-movement of the "line of sight" and of negative after-images under pressure. Since rotation of the eye was assumed, our judgments as to the direction of the "line of sight" could not depend upon the position of the globe in the socket, the tension of the ocular muscles, nor upon the movement of the eye over the surrounding surfaces. That is to say, no afferent sensations arising from eye movements could have a functional value in determining these judgments. Hence "innervation feelings" must exist and possess this function. Most modern writers admit the logic of the situation, but finding no introspective evidence for "innervation feelings,"

[1] *Op. cit.* pp. 743–4.

substitute in their stead images of former movements, attention, etc.

The term "line of sight" seems rather unfortunate in this connection. In our statements the term "point of fixation" has been used. "Judgment as to the line of sight" is apt to imply that our feeling in these conditions is a result of more or less conscious inferential processes. Our purpose is to describe the facts more on the level of immediate perceptual consciousness.

The "line of sight" is not a thing in experience, but a thing cognized or thought of; it is the spatial relationship of the "point of fixation" to the head, more particularly to the position of the Cyclopean eye. On the other hand, the point of fixation is an experienced thing, a unique portion of our visual consciousness, difficult perhaps to describe, but easy to point out and identify. One is never at a loss to discriminate this point from other portions of the visual field. It is the focal point of our visual consciousness, the focus of visual attention, the point of clearest and most distinct vision. Its peculiar and striking characteristics are supposed to be functions of foveal activity, *i. e.*, this particular bit of the visual field is that part of our visual consciousness which corresponds to the fovea.

Consequently the non-movement of the line of sight, or the point of fixation, really means that the conscious object corresponding to the fovea does not change its position in ideal space during pressure or closure. The behavior of foveal negative after-images confirms this position, for they are the psychical objects corresponding to the fovea, and they are always located at the point of fixation. The objection may be made that negative after-images are due to central processes, and hence are not controlled as to location by peripheral conditions. However, any foveal entoptic phenomenon, or any object affixed to the eyeball so as to stimulate the fovea does not move during pressure. The stimulation remains continuously on the fovea, but the corresponding image does not move.

The above statement is true not only for the fovea, but for

any part of the retina, *i. e.*, for the retina as a whole. Any peripherally located negative after-image, the shadows of the blood vessels, and all peripheral entoptic phenomena fail to move. The object affixed to the cornea in the experiment described above occupied about 20° of the visual field, and all parts of this extended image were also stationary. Again, when the stimulation is stationary on the retina, the corresponding image moves with certain eye movements, but is stationary with others. Consequently all the above facts may be stated thus: the visual image corresponding to any point on the retina does not change its position in space during pressure, suction, or closure, but does move with every normal or superimposed rotation.

This statement of the facts at once reduces the question to a theory of localization. The term localization is rather ambiguous in this connection. For instance, many theories of localization have been propounded to account for the inverse relationship between the retina and the visual field. Many of these are anatomical in nature. The ingenious theory has been proposed that the localization of a visual image is a function of the directional position of the rods and cones, the conscious content corresponding to any rod or cone being localized somewhere along the extension of its longitudinal axis. Hyslop [1] offers a similar conception that the localization is along a line perpendicular to the surface of the retina. The projection theory maintains that the localization is on the line connecting the nodal point and the part of the retina stimulated. It is at once evident that any such anatomical theory cannot be wholly right, for in our tests the visual images remained stationary, although the optic axis was deflected as much as 20 degrees. Such theories are useful in accounting for the inverse relation between the retina and the visual field, but do not explain the facts pertinent to this discussion. Our question concerns the localization of the visual field as a whole rather than with the mutual relations of its different parts. Localization is ambiguous in another

[1] Hyslop, Psych. Rev. 1897, p. 142.

respect. In previous descriptions we have referred to the movements, or lateral displacements, of all images in the visual field during pressure or closure. This would seem to controvert our present statement that the localization of images is not disturbed during pressure. In the former case the location of the image which corresponds to some external object is changed, while the localization in reference to the retina is not disturbed. It is this latter meaning which concerns us here, and to avoid any possible ambiguity we shall employ the phrase "retinal space reference" to denote the localization of the visual content corresponding to any specific portion of the retina.

Our facts may now be stated as follows, that the retinal space reference moves with every normal or superimposed rotation, but remains undisturbed during the eye movements produced by pressure, closure, or suction. Our problem is to determine the reason for this difference of behavior in the two cases. Any explanation of the non-movement of the space reference must also explain its movement. What law or principle determines the space relation of the visual field as a whole to the eyes? Why should the visual field be located in front of the eyes rather than to one side of the head? Of what process is this retinal space reference a function?

The question may be regarded from another standpoint. With pressure the image corresponding to any external object undergoes a lateral movement. This illusion is said to be due to the shifting of the stimulation across the retina. In a normal rotation, however, this retinal shift does not produce the consciousness of motion. In other words, no explanation of the pressure illusion is complete and adequate which does not account for the different results of retinal shifting in these two cases. An adequate theory must explain not only the illusion, but also the absence of illusions in other conditions. We ordinarily say that in normal rotations the retinal cue to movement is "corrected" or negated by the eye movement. This is not an adequate explanation, for in the case of pressure and

closure the eye movements do not correct or negate the retinal shift, and an illusion of motion results. "Correction" is not a function of eye movement, but of a process which is present in some movements but absent in others. My contention is that "correction" or "non-correction" are but names for certain results of the movement or non-movement of this retinal space reference. With pressure objects appear to move, *i. e.*, correction is absent, because the space reference of the retina remains unchanged; consequently we have change within a stationary system of spatial relations, and to my mind the consciousness of change within a system of space relations is motion. In the case of the voluntary eye sweep objects appear stationary, or correction occurs, because the space reference of the retina changes with the eye movement, and hence coincidently with and opposite to the retinal displacement of the stimulation. The two factors negate or neutralize each other. Because the space values of our visual processes in reference to the body have been transformed during the rotation, the image of any object maintains the same spatial relation in spite of the difference of its retinal localization. Change in space reference and correction occur in the same eye movements, and are functions of the same process.

With pressure, the images of external objects move while the images corresponding to any portion of the retina — negative after-images, entoptic phenomena, etc. — are stationary. The opposite conditions obtain during voluntary rotations: Images of external objects are stationary while entoptic phenomena move. This conception of a retinal space reference possesses the advantage of grouping these diverse results and allowing of a single principle of explanation, *viz.*, the process of which the space reference is a function.

Since according to this conception "correction" and "non-correction" are certain results of the behavior of the space reference, it follows that a visual illusion must occur whenever there is any discrepancy between the space reference and the position

of the eye, whenever their normal relation is disturbed. Consequently the relation of the space reference to the eye may be stated as follows: —

(a) The space reference changes coincidently with every eye movement wherein no illusions occur; (b) it remains stationary with a stationary eye when illusions are absent; (c) the space reference is stationary with a moving eye in the case of certain illusions, *viz.*, those due to external pressure, closure, suction, jars on the head, extreme peripheral rotations, and autokinetic sensations;[1] (d) the space reference moves with a stationary eye in the case of illusions due to paralysis or paresis of the eye muscles, convergence, and prism distortions.

Any principle of explanation stating the relation of the space reference to the eye must be a universal one. It must apply to all cases equally as well as to the particular case of pressure or closure. A theory applying beautifully to the closure illusion may be totally inadequate to meet the different conditions of the paresis phenomenon and *vice versa*. Consequently all theories as to the behavior of the retinal space reference must be tested by a reference to each of the above illusions. This will necessarily lead us far afield into many controversial domains which at first thought may seem to have no logical relation to the topic at hand. The justification for such a digressive procedure is, I hope, sufficiently apparent without further explanation.

Knowing all the concrete conditions wherein the space reference maintains some discrepant relation to the eyeball, we are n a position to analyze the facts and discover the determining principle.

1. A type of explanation to be ruled out as inadequate is the teleological; that our visual consciousness is located in front of the eyes for advantageous reasons. Any such explanation is valid in its way, but fails to give the mechanism by means of which the result is attained; it explains the results of a function

[1] The reasons governing this selection will be developed later in the discussion.

in terms of utility, but says nothing as to the *modus operandi* of the function itself. It is this latter question which concerns us.

2. As was mentioned, no anatomical theory is adequate, for, with pressure, the eye may be deflected 20 degrees with no change in the spatial reference. In fact, if the visual field had a fixed and constant relation to the eye, no illusions of this sort could occur. The objection may be urged here, as has been done in the case of paresis, that we are neglecting the conditions in the opposite eye; that the two eyes are a single functioning mechanism and that as a consequence the non-movement of the spatial reference of the pressed eye may be due to the stationary opposite eye. However valid the reference to the opposite eye may be with paresis, it certainly will not hold in the case of pressure. One may simultaneously press the opposite eye in any direction without changing the results. The spatial reference of both eyes remains constant, and hence has no fixed anatomical relation to either or both eyes. The same is true of illusions where both eyes move, *e. g.*, the autokinetic sensations. Of course we are assuming that this illusion is due to eye movements — a much disputed point. However, it serves as an illustration. If the spatial reference is stationary, it can have no anatomical relation to either retina.

Eliminating any anatomical theory, at least as a complete explanation, it is evident that we must seek a principle either psychical or physiological connected with eye movements. The spatial reference moves with some eye movements, but does not with others. Our principle of explanation must be one which sharply defines and distinguishes between these two classes of eye movements. An attempt at differentiation may be made in either of three ways; (*a*), the manner in which we are conscious of the movements in the two cases; (*b*), the kind of eye movements, *e. g.*, voluntary, involuntary, or reflex; and (*c*), a statement in terms of some process which is present in the one case but absent in the other, *e. g.*, innervation feelings, memory images, or attention, etc.

3. James attempts the first, a principle of division based upon our consciousness or knowledge of the state of the eye. "The original visual feeling of movement is produced by any image passing over the retina. Originally, however, this sensation is definitely referred neither to the object nor to the eyes. Such definite reference grows up later and obeys certain simple laws. We believe objects to move: (1) whenever we get the retinal movement-feeling, but think our eyes are still; and (2) whenever we think that our eyes move, but fail to get the retinal movement-feeling. We believe objects to be still, on the contrary, (3) whenever we get the retinal movement-feeling, but think our eyes are moving; and (4) whenever we neither think our eyes are moving, nor get the retinal movement-feeling. Thus the perception of the object's state of motion or rest depends upon the notion we frame of our own eye's movement."[1] With a slight change of terminology the same position is re-affirmed later in the same volume (p. 506). Consequently whenever our knowledge or consciousness of the state of the eye is correct, no visual illusions occur, but a false judgment as to the state of the eye will lead to an illusion in the visual field. In our terms, the statement would read: The spatial reference of the retina will follow a moving eye whenever we know that the eye really moves, and will remain stationary when we think the eye is stationary. If the eye be stationary, the spatial reference will be stationary when we think the eye is not moving, but will move when we think the eye is moving. The spatial reference is thus a function of what we think in regard to the state of the eye.

Several objections may be made to this formulation. At first one may gain the impression from this statement in overtly conscious and intellectualistic terms that the perception of the object's motion is made the result of more or less conscious

[1] James: Principles of Psychology, vol. 2, pp. 88–9. The four statements are here numbered not as in the James text, but in consecutive order for purposes of reference.

inferential processes based upon our immediate consciousness of the two factors, the eye movement and the retinal movement-feeling. In our adult perceptions of motion, if any factor is immediate and given and not a result of conscious mediatory processes, it is the consciousness of the object's motion. If any factor be mediated and inferential, it is the consciousness of the state of the eye.

James' formulation, I take it, refers not to adult perceptions of motion, but rather to their genetic development. But in this respect his statements are strikingly and exasperatingly illogical. I shall attempt to transpose and rearrange the above quotation so as to expose its inconsistency. The same numbering of the four principles will be used here to facilitate a direct comparison in the two cases. "Originally we have a mere visual feeling of motion, an objectless thing. As yet we do not know whether the eyes or the objects move. Finally we project or fasten this mere movement-feeling on either the eyes or the object according to certain principles. Before we know whether the eye or object moves (3) we fasten this movement-feeling on the eyes, whenever we know that the eyes move, and (1) project it on the object whenever we know that the eyes are still. If we do not have this primitive movement consciousness to project, nevertheless (2) we judge that the object moves whenever we know that the eye moves, and (4) think that the object is stationary whenever we know that the eye is stationary." Knowledge as to the movement of the eye is presupposed as the means by which the primitive movement consciousness is fastened on the eye or the object as the case may be. Such a statement of the principles at least brings out the fact that consciousness of the eye movement is the principle of demarcation.

A more serious objection is that the principle fails to meet all the facts. Recent photographic tests have abundantly demonstrated that the eyes are never at rest during fixation of a stationary object. Slight reflex excursions persistently occur, and as a consequence the stimulus is shifted over the retina. According

to the first principle illusions should occur, for we think, or at least have thought, that the eye is stationary. We are entirely unconscious of these movements. Dodge[1] has demonstrated the existence of many reflex deviations where the eye attempts to follow a moving object. Here slight retinal shiftings occur, we are unconscious of these reflex deviations, but no consequent illusions result.

4. The fourth type of theory would attempt to make this spatial reference a function of some physiological or psychical process connected with eye movements, *e. g.*, afferent sensations. James' theory of "consciousness" or "knowledge" reduces itself to the afferent theory. In the above treatment he nowhere specifically mentions the process or means by which we become conscious of the eye movement. In his treatment of paresis, however, he definitely refers to the afferent sensations of the opposite eye as affording his principle of explanation, and we must insist that all these cases belong to a single class, and must find a single principle of explanation.

In regard to the Müller-James reference to the afferent sensations of the opposite eye as an explanation of the case of paresis and convergence, it is well to note that such argument proves nothing definitely, even against the innervation theory. It merely points out that the "innervationists" have neglected one possibility of explanation; that the illusion may be due to the afferent sensations of the moving eye. True, but it also may be due to the innervation of that eye, so far as possibilities are concerned.

The "afferent sensation" theory fails to meet the facts in the case of these reflex movements detected by photography. Introspection gives no clue to any afferent sensations in these cases, and yet the spatial reference moves as ordinarily. It may be objected that the sensations really exist and function as usual,

[1] Amer. Jour. Physiology, viii, 1903, p. 307; Psychol. Rev. xi, 1904, p. 1. Cf. also, Holt, Harvard Psychol. Studies, i, 1903, p. 1; McAllister, Yale Psych. Studies, i, 1905, p. 17.

but are below the limen. However, one may as well drop the term "sensation" and admit that the afferent processes are purely physiological. In fact I would offer no *a priori* objection against the contention that physiological processes could perform the function. But if true in this case, no illusions at all should occur, for there is no conceivable reason why afferent physiological processes should be present with some rotations, but absent in others. Such a theory would meet exactly the same difficulties as an anatomical theory. No illusions could occur. Not even a reference to the opposite eye could be urged in all cases.

With pressure the eye moves, but the spatial reference is stationary although afferent sensations are present. The objection may be made that this movement is not a normal rotation. True, but the spatial reference changes with a superimposed rotation, and the resulting afferent sensations are no more "normal" than in the case of pure pressure. The eye simply shifts from one abnormal position to another abnormal position. Moreover, the actual amount of eye movement during a superimposed rotation is not so large as the corresponding movement of the spatial reference. In normal rotations, the spatial reference and the eye move together, the two movements expressed in degrees being identical. This is not true for superimposed rotations, for a shift of 10° in the position of the optic axis will be accompanied by a 12°–13° movement of the fixation point, or spatial reference. This extra movement of 2°–3° will be the same as the extra displacement of the visual field due to a superimposed rotation. For instance, let there be two objects *A* and *B*, 20° to the right and left of the zero point respectively. Let subject 1 fixate *A*, and with pressure produce a 5° displacement to the right. Maintaining the pressure, the fixation is changed to *B*, a distance of 40°. Visual objects are now displaced 5° to the left. During the superimposed rotation, the displacement has changed from 5° right to 5° left, an amount of 10°. The actual deflection of the optic axis during this superimposed rotation has been 30°, while the spatial reference has changed 40°.

The actual discrepancy between the two values varies with individuals and with the degree of pressure in the same individual.

But here the objection may be made that we are forgetting the conditions in the opposite eye, which normally rotates exactly 40°. This is true; but if I now press on this eye so as to produce a similar 5° displacement, the conditions will not be altered; the spatial reference of both retinae will move 40°, while both eyes will rotate abnormally but 30°. With pressure, no appeal can be made to the opposite eye, no matter what theory is advocated.

5. In eliminating the afferent theory, all afferent processes whether psychical or physiological are included. This leaves only efferent processes to be considered. As to "memory images" resulting from former eye movements, one is hardly disposed to assign them a function denied to the afferent sensations of the movements themselves. Moreover, they can hardly be supposed to be present in all cases where the spatial reference is known to move, *e. g.*, involuntary rotations and the reflex movements detected by photography. They are only supposed to be overtly present in the case of definitely voluntary movements. To claim that the memory images are unconsciously present in involuntary and reflex rotations is a desertion of the theory and equivalent to making the spatial reference a function of the physiological innervation of the ocular muscles.

6. Hering[1] is an upholder of the "attention" theory. Changes in "die absoluten Raumwerthe der Netzhaut" are due to changes of the attention. In paresis, the attention moves, or turns, to the right and carries the spatial reference with it. Illusions due to eye movements arise because the retinal shifting is not compensated by a change in "die absoluten Raumwerthe." The spatial reference has not changed because the eye movements have been initiated, not by a change of attention, but by other unconscious processes (nicht durch den Ortwechsel der Aufmerk-

[1] Hermann, Handbuch der Physiologie, vol. 3, 1, pp. 534–5.

samkeit, sondern durch andere unbewusste Vorgänge). This conception and systematization of the facts is similar, if not identical, to that outlined above. It schematizes everything under "die absoluten Raumwerthe der Netzhaut" or, in our terms, the spatial reference of the retina, but makes this a function of attention.

"Change of attention" does not mean any change, but a spatial change of the visual attention (Ortwechsel oder Ortsveränderungen der Aufmerksamkeit). Obviously the spatial reference would not be altered by a change from the visual to the auditory type of attention nor by any change from one process to another within our total eye consciousness. Attention is not a specific process over and above the afferent and efferent visual activities; it is rather the mode in which these latter operate. If we abstract from our ocular experiences, the visual field, the afferent sensations from the muscles, lids, and sclerotic, and the images involved in voluntary control, there is no attentive process remaining. Such an attention theory would have no claim to validity. The changes of attention, according to Hering, seem rather to be changes which involve our eye consciousness as a whole in its spatial significance. In this sense the theory has a possible validity, for it may well be that the spatial reference is not a function exclusively of any one process connected with eye movement, but rather of several or all such processes functioning as a whole in their spatial signification.

My objection to such a conception is that the spatial reference is thus made a function of a phenomenon of which it is an essential and integral part; it attempts to explain a thing largely in terms of itself. One voluntarily changes the visual attention to a new spot in space either by imaging this spot or object, or by peripherally attending to it. That is, the complete change of attention is thus initiated and controlled. But suppose that one attends as much as possible to the new point without allowing the eyes to perform the corresponding rotation; the spatial reference does not change, but remains stationary. The atten-

tion is at least partly changed to the new position, but the spatial reference has not been altered even in part. The adherents of the theory can claim that when the attention does fully and completely move to the new point in space, the spatial reference will be correspondingly altered. This is true as a matter of fact, but I would deny the implied causal nexus. It is much nearer the truth to hold that the attention has become fully centered upon the new object, because the spatial reference, or point of fixation, has moved, than vice versa. The point of fixation is *per se* the focal point of the visual consciousness. Complete change in the attention and the movement of the point of fixation are different ways of describing the same fact. Especially is this true in the case of reflex rotations; here changes in the direction of the visual attention and movements of the fixation point are identical phenomena. Obviously to explain one in terms of the other would be mere logomachy.

7. This paper offers an explanation as follows: that the spatial reference is a function of the physiological innervation of the ocular muscles, that the spatial reference moves in all cases where the rotation is initiated from within, *e. g.*, voluntary, involuntary, and reflex movements, but is stationary in all cases where the eye movement is a result of extraneous forces such as lid and finger pressure, muscular fatigue, bodily movements, etc. Obviously the different behavior of the spatial reference could not be due to the kind of rotation *per se*, but to a specific process present in the one case and absent in the other, the process of innervation. This function is assigned to the physiological impulse because (1) introspection gives no evidence for the existence of an "innervation feeling," (2) as was shown before, the distinction cannot be stated in terms of consciousness and unconsciousness, and (3) there is no factual warrant for the prevalent assumption that a physiological process cannot function to determine the nature of one's consciousness unless it be directly represented in consciousness by a separate and distinct psychical content of its own.

This conception is a combination of the Hering and Helmholtzian theories. With Hering it groups these illusions in a class by the term "retinal space reference" or "die absoluten Raumwerthe der Netzhaut," making possible a single explanation. With Helmholtz, it makes the space reference a function of innervation. In this respect it is the "innervation feeling" theory shorn of the feeling or psychical part. This conception possesses all the logical advantages of the Helmholtzian theory in meeting the facts, but is free from any introspective objections. The validity of this conception must be judged from the subsequent argument.

As to the facts, we know that the spatial reference of the retina changes at least with most voluntary, involuntary, and reflex rotations. If any demarcation can be made at all in terms of the kind of eye movement, it must be at the point indicated. Such a principle of division obviously holds in the case of closure and finger pressure. Here the eye movements are due to extraneous forces acting upon the globe, while the superimposed rotations on the other hand are due to innervations of the ocular muscles.

The application of the principle to the remaining illusions is not so self-evident because of our ignorance of the causal factors in many cases. We are concerned only with those illusions due to eye movements, but because of the lack of definite and decisive knowledge there is a wide divergence of opinion as to the cases to be explained in this way. Obviously it will be somewhat futile to discuss all the reasons for and against the eye movement hypothesis in each case, and our selection must be somewhat arbitrary, frankly admitting that it is largely a matter of conjecture and assumption. However, one principle of selection is evident if our former positions be true, *viz.*, that illusions due to eye movement must affect the whole of the visual field. Again our selection will be confined to those cases upon which there is some unanimity of opinion among writers.

As to "autokinetic sensations" there is some divergence of

opinion. Exner [1] has proposed a retinal explanation, a theory formulated from some tests on the "creeping-insect" phenomenon. The theory seems legitimate in the latter case, but its extended application is hardly necessary or justifiable.

The essential and general facts in regard to "autokinetic sensations" are these: (1) The fixation object is an isolated light of weak intensity; (2) the direction of the movements depends upon the position of the fixation in the field of regard. Generally the direction is peripheral as in the case of winking; (3) the length of the movement varies with different subjects and circumstances. The movements may attain a length of 30°; (4) the movements probably refer to the entire visual field. Bourdon [2] has secured movements of a circular object, 25 cm. in diameter, at a distance of 1 m. Such a diameter would represent at least 60° of the visual field; (5) the movements are apparently binocular; (6) the apparent fixation remains stationary [3] as in the case of pressure and closure; (7) the light generally moves a certain distance, and then remains stationary. Sometimes it moves back to its original position; (8) weak illumination and especially fatigue favor the rapidity and length of the movement and the appearance of the phenomenon.

The similarity of these movements to those of winking, especially binocular closure, is most striking, but even a closer relationship can be established by recalling a former description of image displacements in extreme rotations (p. 36). The writer cannot maintain unity of vision with extreme peripheral fixation positions. All visual objects of one eye are displaced peripherally, although its retinal reference as tested by the fixation point and negative after-images is not disturbed, coinciding with that of the opposite eye. With less peripheral positions, the displacement does not occur at first, but only after prolonged fixation. As fatigue becomes more and more pro-

[1] Exner, Ueber autokinetische Empfindungen, Zeit. f. Psych. xii, 1896, p. 313.

[2] Bourdon, La Perception Visuelle de L'Espace, pp. 333–342.

[3] Sanford, Experimental Psychology, p. 309.

nounced, the movements occur more readily, increase in length and rapidity, and are present for positions where ordinarily unity of vision can be easily maintained. With fixation positions in the right upper quadrant, I have finally succeeded in obtaining displacements of 3°–5° for the left eye where the fixation was but 25°–30° from the primary position. The fatigue was so marked that its effects were noticeable for a couple of days. The introspective feeling was clear cut and distinct; the eye *felt* as if slowly rotating back toward the center of the field. The difference between these movements and autokinetic sensations is but slight; in our tests the movement is limited to the images of one eye, and normal conditions of illumination are present. The autokinetic movements refer to the images of both eyes and the light intensity is so weak that no other objects in the visual field are visible.

I would explain these cases as follows: Owing to the form of the eyeball and the position of its center of rotation, the front part of the globe must be strongly pressed against the surrounding elastic tissues in extreme rotations. Thus this resistant force of the fatty tissues and the elasticity of the antagonistic group of muscles are exerted against the force of the contracting muscle group. When, for any reason whatsoever, the contractile force becomes less than the two antagonistic mechanical forces, the eyeball will necessarily be forced back toward its central orbital position. This return rotation being due to extraneous mechanical forces, the spatial reference (point of fixation and negative after-images) will remain stationary, while consequently visual objects must move in a direction opposite to this forced rotation, *i. e.*, toward the periphery of the visual field. Now the two mechanical forces opposed to the rotation will evidently increase in intensity as the eye is rotated peripherally. In the case of extreme rotations where unity of vision is no longer possible, the mechanical forces have increased to such an extent that they are greater than the contractile force. In proportion as the contractile muscles become fatigued, the same amount of innerva-

tion will become less and less effective, and consequently the phenomenon will occur for fixation positions nearer and nearer the center of the field. Fatigue will rapidly increase during a constant fixation, and thus the displacements may only occur after the fixation has been maintained for some time. If this explanation be true, the question may occur why one cannot voluntarily increase the innervation and overcome the opposing mechanical forces. One can to some extent in horizontal positions where the increased voluntary innervation is convergent in nature, but it is impossible for positions in the upper part of the field. The innervation mechanism is a unitary affair; one cannot voluntarily increase the innervation in the displaced eye alone, any more than one can voluntarily rotate one eye upward and keep the other stationary. The convergent mechanism, however, is such that either both eyes or only one eye may participate in the unitary convergent motion. The autokinetic movements occur much more readily and are participated in by both eyes because of the weakness and intermittence of the physiological innervation due to the extreme weakness of the sensorial stimulation. The continued force of a contraction depends upon afferent as well as central conditions. One does not maintain a constant fixation of an object merely by a continuous centrally aroused innervation. All the physiological forces set free by the retinal stimulation are directed or focused on the contracting ocular muscles. Volition also comprises the directing of this sensorially given energy toward a given end. Consequently the displacement should occur much more readily when a very small and weak light is the only object visible. As a matter of fact we know that the autokinetic phenomenon does occur the more readily as the size and illumination of the object are decreased. Disregarding any factual considerations, such an hypothesis explains very satisfactorily the main characteristics of the two phenomena, the direction of the movements and the varying influences of fatigue and intensity of illumination.

Another observation is noteworthy. In the monocular displacements due to prolonged fixation, the subject was distinctly aware of the eye movement as a rotation toward the center of the field. This is the direction necessary to assume in order to explain the direction of the image movement. If the assumption be true, the introspective fact is another proof of our position that the movement of the spatial reference cannot be stated in terms of one's consciousness of the ocular rotations. In this connection it might be well to note that the spatial reference changes during sleep, for it is hardly possible that the eyes are stationary during the night. Yet we have no consciousness, or knowledge, as to the state of the eyes.

Paralysis presents the converse case of a change of spatial reference with a stationary eye. Since the eye is motionless, the fixated object continues to stimulate the fovea, but the corresponding consciousness moves in the direction of the attempted rotation. The James-Müller contention holds that this illusion may be a function of the afferent sensations of the opposite eye. This is true, but also it may be due to the innervation of the opposite eye, or rather of both eyes, for the innervation is a unitary binocular process. The question at issue is not what explanation is possible in this particular case, but in all cases of the movement or non-movement of the spatial reference. The same principle of explanation should hold throughout. The reason for rejecting the afferent sensation theory is not its impossibility in paralysis and paresis, but in other cases.[1] Our purpose is to demonstrate the possibility of the innervation theory in all cases. Very obviously such an explanation is possible in paralysis and paresis.

The usual statement of the convergence phenomenon is as follows: Place two objects at different distances in the line of sight of one eye. Close the opposite eye and change the accom-

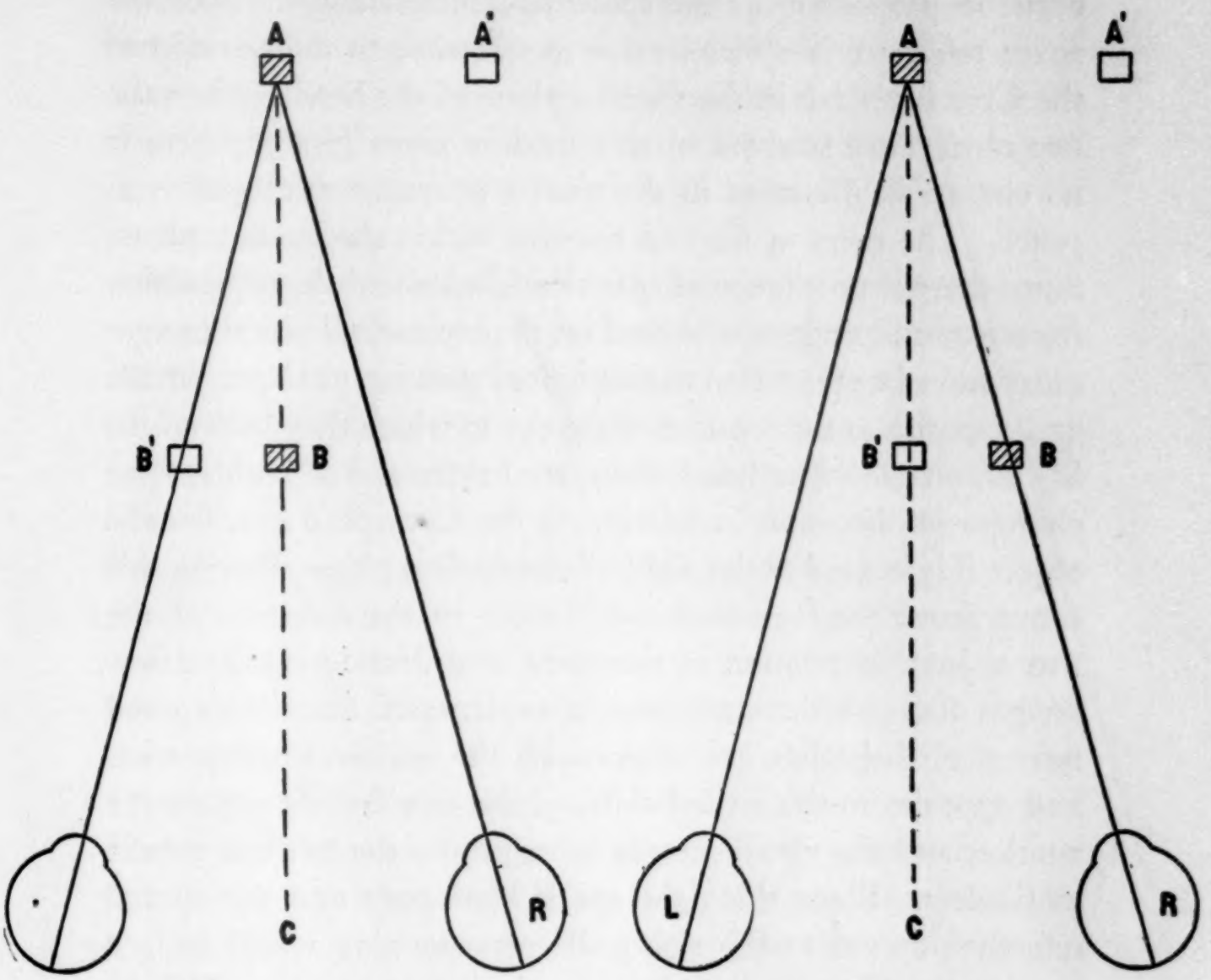
[1] Wundt has denied the possibility of the afferent sensation theory even in paralysis and paresis. His objections are based upon certain facts in the paresis phenomenon itself. See Physiologische Psychologie, v. Auf. ii, p. 27 ff.

modation from one object to the other. Both objects, and in fact all objects in the monocular field will move in the direction of the convergent rotation of the closed eye. Since the open eye does not rotate, there is no retinal shifting of the stimulation from external objects. Yet the visual image corresponding to any object or any spot on the retina has moved. The point of fixation and monocular negative after-images behave similarly. In other words the spatial reference of the retina changes concomitantly with the convergent rotation of the closed eye. Is this change a function of afferent sensations or of the innervation?

Whatever the explanation may be, the fact itself is no isolated phenomenon peculiar to these conditions. It is but a special case of a general phenomenon present in every convergent act. It is not at all necessary for the two objects to be located in the line of sight, nor for one eye to be closed. Let two objects *A* and *B* be situated in the median plane of the head with the fixation directed at *A* (fig. 9). Object *B* appears doubled, the right eye's image being located at *B'*. By converging from *A* to *B*, the image *B'* will move to *B*, and *A* will become doubled, the right eye's image moving to *A'*. All visual images belonging to the right eye have moved to the right, *i. e.*, in the same direction as the convergent rotation of the opposite eye, as in the special case formerly cited. The same statement holds for all images belonging to the left eye; they will move in the same direction as the rotation of the right eye. It is to be noted that in this case the movements of the two fields are equal in amount.

Let *B* now be situated in the line of sight of the right eye (fig. 10). Convergence from *A* to *B* will cause the right eye's image *B'* to move to *B*, and of *A* to move to *A'*, *i. e.*, all visual images belonging to the stationary right eye will move with the left eye. The images belonging to the moving left eye will not move however, and the amount of the movement of the right field will be equal to the combined movements of the two fields in fig. 9. Now if *B* be gradually moved to the left, the movement

of the right field will gradually decrease in amount while that of the left field will increase, until the two amounts will be equal when *B* attains a position in the median plane. As *B* is moved to the line of sight of the left eye, the movement of the right field will decrease to zero. Thus the combined movement of the two



FIGS. 9 and 10.

A C, median plane of the head; *A*, *B*, fixated objects; *A'*, *B'*, right eye's images.

fields is constant in amount, while the movement of either field varies from zero to the constant *x*. The amount belonging to either field is proportional to the relative amount to which the opposite eye participates in the combined convergent rotation. In other words the movement of either field has the same direction as and is proportionate in amount to the rotation of the opposite eye.

These illusory movements can be nicely stated in terms of the movement and non-movement of the spatial reference. If the eye rotates, illusory movements must occur unless the retinal shifting be negated by a corresponding change of space values; if there be no rotation and no retinal shifting, an illusion will occur in proportion as the space reference changes. Now the space reference is a localization in reference to the position of the Cyclopean eye in the median plane of the head. When the two objects are situated in this median plane (fig. 9), there is no change in direction in the spatial reference during convergence. The point of fixation remains within the median plane. Since there is no change of spatial reference and the stimulation from external objects is shifted on the retinae, all visual images must move in proportion to this retinal shifting, or in proportion and opposite to the rotation of the eye to which they belong. In fig. 10, on the other hand, the spatial reference of both retinae changes its direction in relation to the Cyclopean eye, for the object *B* is located to the right of the median plane. During this convergence one feels such a difference in the direction of the two objects in relation to the body, and foveal negative after-images also give the impression of movement. Since the spatial reference of the left eye moves with the eye, or in proportion and opposite to the retinal shifting, the two factors negate one another and the visual images belonging to the left eye appear motionless. Since the right eye is stationary and the spatial reference moves to the right, all corresponding visual images must move likewise. Such a conception states these illusory movements in terms of the corresponding and not of the opposite eye, as the afferent sensation theory would need to do.

Hitherto we have spoken of the spatial references of the retinae as though they were two independent, unrelated phenomena. As a matter of fact there is but a single space reference; the phenomenon is a unitary binocular affair; there is but one point of fixation. In all the tests described there has been no dissociation of the space reference of the two retinae.

If one eye be pressed, its foveal consciousness is still combined in space with the foveal consciousness of the opposite eye. The same is true if both eyes be pressed simultaneously, or if one eye be rotated out of the horizontal plane by fatigue. The space significance of the two retinae still maintain their normal relationships to each other. It is a dictum of psycho-optics that the two foveæ always give unitary vision and that binocular foveal after-images can never be spatially dissociated. This fact of the unitary space reference of the two retinae would strongly suggest that the phenomenon is a function of some unitary binocular process, as innervation.

Moreover, we have hitherto used the term "change in space reference" as a change in direction. Where the two objects are located in the median plane (fig. 9), no such directional change is present. Yet innervation is present, and apparently this fact is contradictory of our general position that change of space reference is a function of innervation. As a matter of fact, during convergence the space reference does change in relation to the position of the Cyclopean eye, but the relation is one of *distance* and not of *direction*. Consequently our general position is true, only one must add that the change is one of distance in so far as the innervation is convergent in nature. Obviously this proviso does not detract from our statement of the above illusions in terms of " change of space reference," for the phrase was there used in its *directional* signification.

The recovery of unitary vision after introducing a prism in the line of sight of one eye is interesting in this connection, especially the case where the image deflection is in a vertical direction. Suppose one fixates an object and brings a prism before the right eye so that its image of the object is deflected upward. After a time the two images move together and combine. How does this readjustment take place? Two possibilities are conceivable; (1) that there are two space references which usually but not always have a fixed relation to each other, and that both of these have changed, or one has changed, so as to

effect a recombination of the visual images without any rotation on the part of either eye; and (2), that there is but one space reference and the recombination is effected by a rotation of one or both eyes. In the latter case the question arises as to whether the space reference is modified during this readjustment of the eyes. The usual answer is that the right eye rotates in this case because double images again appear when the prism is removed. Such a proof, however, is insufficient for it does not obviate the first possibility. We shall maintain that the left eye is stationary while the right eye rotates upward, or in the direction of the image displacement, that the space reference is a unit, but that it moves more or less during the new adjustment of binocular conditions. The rotation may be proved by holding objects in the line of sight of each eye. The objects should be as near the eye as possible, the right one being between the eye and the prism. If any rotation be present, a monocular parallax will occur, showing the presence and direction of the rotation. In the recombining adjustment there are never two points of fixation, whether simultaneously or alternatively. After the recombination, the visual object is located at the point of fixation. Foveal after-images belonging to either eye are always located at this point of fixation, showing that the object stimulates both foveæ. A binocular after-image is not separated during this readjustment. Evidently this rotation of the right eye has been executed reflexly, and since the binocular conditions of innervation have been modified, it would seem that some change of space reference should occur. Now if the space reference be stationary, only the right eye's image of the object should move during the recombination. If the space reference moves in proportion to the rotation of the right eye, the recombination should be effected entirely by the movement of the left eye's image. If the space reference changes only partly so as to be located, as it were, half way between the position of the two eyes, then both images should participate in the reuniting movement. This latter condition obtained with most subjects

tested; the image belonging to the right eye would be deflected upward and be perceived peripherally. The fixation would remain with the left eye's image. In the recombination the right eye's image would move down and the point of fixation and the left eye's image would move upward. It will be recalled that in the recombination of doubled images in normal convergence sometimes both and sometimes only one of the images participates in the combining movement. However, with these subjects if the prism deflection be horizontal so that the recombination be convergent in nature, both images always participate in the movement, a fact which indicates a real shift in the space reference. Moreover, if one attempts a localizing movement after the recombination, errors will occur in the direction of, and in proportion to, this shift of the space reference. In other words, this reflex rotation of one eye has tended to carry the space reference with it. One subject (F. M. H.) was known to be strongly right eyed, and gave peculiar results. The right eye's image was always stationary, and the recombination was effected by a movement of the image belonging to the left eye, no matter which eye was subjected to the rotation. That is, the right eye controlled the space reference; if the left eye were forced to rotate the space reference was stationary, but if the right eye rotated the space reference moved proportionately. Localizing movements were governed accordingly. Moreover, in the particular case where the right eye's image was deflected upward not more than a degree, doubling rarely occurred, for both images would be deflected up simultaneously. The shift of the space reference and the consequent movement of the left field would occur practically instantaneously.

We have remaining a series of illusions due to shocks and jars of the head and body which are probably embraced by our formula. A vigorous blow on a ruler held firmly between the teeth, a blow on the cheek bones, strong voluntary jerks of the head, etc., generally cause quick but small illusory movements of visual objects. If light finger pressure or the mere pressure

of the closing lids be sufficient to produce marked eye movements of 3°–4°, it is entirely possible that such mechanical jars should slightly disturb the position of the eye despite its elastic surroundings. In these tests the negative after-image is approximately stationary, though moving slightly in a jerky manner. This is probably due to a disturbance in the innervating conditions. However, the visual object moves much more than the negative after-image, and this difference of movement I am inclined to ascribe to the jar on the basis of our general formula. Accurate observation is extremely difficult in these conditions, and it is possible that the illusions are similar in character to the Purkinje dizziness phenomenon.

The Purkinje illusion at first sight seems to contradict our hypothesis, for eye movements occur, and the illusion refers to the entire visual field. After a bodily rotation to the left, the field first moves slowly to the right and then suddenly jumps back to its original position, the process being repeated for some time. The eyes behave similarly, but rotate in a direction opposite to the image movements. The space reference changes with the rotation, as can be demonstrated by the movements of negative after-images. The movements of the visual object and the after-image are apparently simultaneous, of the same amount, but opposite in direction.

These eye movements can hardly be due to the momentum acquired from the bodily rotation. This might explain the first slow movement, but obviously it could not account for the return jerks, nor for the successive slow movements for such a considerable period of time. Moreover, some proof of a reflex origin can be given. During rotations of the head and body nystagmatic eye movements are present. The eyes first slowly rotate in a direction opposite to that of the body rotation so as to fixate some object. Then the eyes suddenly jump in the same direction as the body movement and fixate an object as before. These alternating eye movements are repeated throughout the

rotation. Stein [1] has shown with a high degree of probability that these nystagmatic rotations are reflexes due to stimulations arising from the semicircular canals. The eye movements after the body rotation are exactly similar in character to these nystagmatic movements occurring during the rotation except that they are opposite in direction. Now after the body is stopped the semicircular canals will be probably subjected for some time to a stimulation opposite to that which occurs during the rotation, and hence produce the nystagmatic eye movements described. Whether this view be correct or not, we are interested in maintaining the reflex nature of the movements in question, for the space reference changes with them. If they be reflex, the movement of the space reference would agree with our formula, while if they be due to extraneous forces the case would be an exception to the theory.

However, if it be granted that our formula covers the facts so far, another difficulty immediately arises, for according to our position no illusions should occur when the space reference changes proportionately to the eye rotation. Either we have an exception in this respect, or the illusion is of a different kind, and is to be explained in a different manner from the illusions previously noted. In fact there is much to support the latter contention.

Helmholtz has described the pressure illusions as resulting from an error of judgment as to the direction of the line of sight, or, in our terms, the directional position of the foveal consciousness in reference to the head. The term "error of judgment" is not applicable to the phenomenon, for the relationship between the point of fixation and the head is a purely psychic relationship, and we are just as sure and certain of the relation during pressure as we are during normal perceptions. Our whole space feeling is as clear cut and distinct as in normal conditions. The illusion is not due to any misapprehension of the space relations,

[1] Stein. Ueber einen neuen Selbständigen, die Augenbewegungen automatisch regulirenden Apparat. Centralbl. f. Physiol. 1901, xiv, 222–230.

but arises simply because the visual images are not located as usual on account of the abnormal position of the eye.

On the other hand, the term "error of judgment" is applicable to the Purkinje phenomenon, for our feeling as to space relationships is entirely different in the two cases. Here the movements of the visual objects do appear illusory in nature. Objects appear to move without getting anywhere. Everything appears hazy, unreal, and kaleidoscopic. Our feeling of localization and space relationships is confused, uncertain, disorganized, and jumbled. Nothing feels clear cut, stable, and definite. If the pressure case be an illusion, the dizziness phenomenon may well be described as an illusory illusion, for the psychical attitude as to space relationships is markedly different.

Our consciousness as to the spatial relationship between the point of fixation and the head is a bipolar affair, and any uncertainty, doubt or disturbance in the sense of the head position will disturb our consciousness of this relationship and produce illusions. This, I take it, is what occurs in dizziness. The head and body sway from side to side, the normal coördinations of equilibration are violently disturbed, and the subject may even topple over in a heap if the dizziness be intense. The head whirls and swims. Our sense of bodily position becomes jumbled and topsy-turvy. Everything swims and swirls; nothing feels fixed and stable. Such a disturbance in the head end of the psychic relationship is sufficient, I should hold, to account for the illusion in question, and furthermore the hypothesis of such an origin would best explain the peculiar swirling and illusory character of the movements in question.

Having connected the space reference with the fact of innervation of the ocular muscles, the function has been assigned to the physiological process for the following reasons: (1) the writer finds no introspective evidence for the existence of an "innervation feeling" in the older sense of the term; (2) the contention is advanced that the demarcation between the two cases

of the movement or non-movement of the spatial reference cannot be made in terms of consciousness. The reasons for this view have already been given (p. 88). Consequently if the space reference depends upon innervation, it must be a function of the physiological process; and (3) it is denied that there is any valid *a priori* objection to assigning a psychical function to a purely physiological process which does not possess a corresponding sensory content of its own.

This latter position demands further discussion. When the "innervation feeling" was banished from psychology, the further step was made of denying any psychological significance to the corresponding physiological process. The motor impulse, *i. e.*, the motor part of the sensori-motor circuit, was banished from the province of psychology along with its previously supposed conscious correlate. The reason for this step seemed to be based upon the tacit assumption that a physiological process could not function to determine the nature of consciousness unless it were represented in consciousness by a corresponding sensory content of its own. This assumption probably had much to do with the long insistence on the existence of innervation feelings. Logically the facts seemed to show that innervation did possess a function, and consequently it must possess a corresponding feeling, for how could it operate on consciousness unless it be a conscious as well as a physiological process.

This assumption is a peculiarly pervasive one, and we find it very prevalent in many phases of psychological theory: it is always tacitly made, never overtly stated and defended. It permeated the older atomistic associationalism which substituted logical for psychological analysis. Logically it is clear that our past perceptions have functioned in our present recognition, and hence memory images representing those past perceptions must be overtly present in the recognitive consciousness. The same was true of perception, which was analyzed as consisting of the present sensory content plus an aggregate of memory images representing past experiences with the object. Meaning,

or logical content, must be constituted by psychical content. Accurate introspective analysis has rendered such a position untenable in the realm of central processes and contents, but the same assumption is now made in regard to peripheral processes. The assumption is found in nearly every treatise on the visual perception of space and motion; eye-changes can possess but little significance in making us aware of external differences simply because we are not conscious of these changes as eye changes. Convergence can have little to do with the perception of depth, because we can discriminate differences in depth without becoming consciously aware of the corresponding convergent activities. Rotation cannot function in the perception of motion because our sense of differences of position is more acute than our sense of the corresponding changes in eye position. In other words, an eye process cannot mediate an external result unless we be definitely aware of the mediating process *per se*. Likewise one might as well argue that binocular disparity can mediate no sense of solidity, unless we be conscious of the disparity, as disparity.

Pushed to its extreme as a universal principle, the assumption simply means psychological atomism. It means that any conscious state or condition must always find an explanation in conscious terms; that consciousness is always to be explained in terms of itself and never in terms of physiology, or brain process. Why should one ever invoke the aid of a brain process as an explanation, if this process could not fulfill its assigned function unless it possessed a corresponding psychical content? Obviously the psychical content itself would be sufficient, and the physiological process a useless luxury. Of course there is no *a priori* reason why this assumption should not be true, but as a matter of fact psychology has found it impossible to explain consciousness always in terms of itself. Physiological psychology finds its main justification for existence in this fact, a fact which is sufficient proof against the universal validity of the assumption, and which indicates that many physiological processes

while having no corresponding contents still do operate in determining the nature and attributes of the contents in consciousness.

Our purpose is to point out that this assumption has no theoretical or factual basis and to challenge its application to any particular case as an *a priori* principle. To use current phrases it is a *mere* assumption. It is not maintained that the assumption is never true in any particular situation, and that a denial of its universal validity gives any positive support to our position. We merely deny that it possesses any relevancy as a positive or negative argument. Each case must be empirically settled on its own merits, free from the weight of any *a priori* objections. The long banishment of the motor impulse from psychology renders one peculiarly unable to grasp the opposite point of view, and yet we must insist that there are no valid reasons for not assigning it a psychological function except factual ones. The banishment was first made because of an unwarranted assumption.

The earlier theories of brain localization attempted to state the brain correlate of any sensory content entirely in terms of a definite isolated cortical area, and hence dependent in no respect upon other areas. Some recent views ascribe the characteristics of a sensory content not merely to its corresponding brain area, but to this in its functional relations to other areas. The content is thus due mainly to the action of some area, and partly to the action of the brain as a whole. Functional coöperation and mutual interdependence of part and whole are thus emphasized. This banishment of the motor impulse from psychology belongs to the older type of theory, for it divides the nervous mechanism in two, confining psychology entirely to one half. Of late there has been a marked tendency to recall the motor impulse to psychological service. Judd frankly takes this position in a recent article on Movement and Consciousness,[1] in which

[1] Yale Psych. Studies, N. S. vol. i, No. 1, p. 199. Psych. Rev. Mon. Sup. vol. vii, No. 1.

he reviews similar positions held by Dewey, McDougall, and Münsterberg. We are here concerned not with the particular theories advanced, but with the general tendency manifested.

So far we have been concerned only with the relation of the space reference to the ocular muscles. Since the visual field moves with every head and body rotation, the question arises as to whether the space reference is also a function of the innervation of other muscles. Such a position, however, is not necessary, for we have defined the space reference as a localization in reference to the head, and not to external objects. Hence if the space reference has a given relation to the head, the same relation will still obtain after a head or body rotation. The space reference will meanwhile have moved only in relation to external space, and not in relation to the head. Movement of the space reference in our sense of the term means a change in relation to the head.

To summarize: the spatial reference of the retina means the localization of the visual content corresponding to any point on the retina, and a localization in reference to the position of the Cyclopean eye. This space reference is a unitary thing, and is a function of the physiological innervation of the ocular muscles. The space reference will change in relation to the head with every change of innervation. This change may be either in direction or distance. The change is one of distance in so far as the innervation is convergent, and one of direction when it is synergic. By synergic is meant an innervation producing parallel movements of the eyes. We have attempted to group a class of illusions under the principle of a directional change of the space reference.

Illusions will occur whenever the eyes and the space reference do not move concomitantly, when either eye rotates when the space reference is stationary, or when the space reference changes while the eye is motionless. In other words, illusions must occur when there is any discrepancy between the innervation and the eye movement. This conception of the phenomena

is advanced as a hypothesis, and not in the spirit of dogmatic certainty, for we are keenly cognizant of the many factual difficulties which may be urged against the formulation. However, to the writer, the objections seem less serious than those which may be urged against any other theory.

In making the distance relation of the space reference to the head a function of the convergent innervation, I have no intention of prejudging the question as to the relative importance of convergence and accommodation in the perception of depth. By convergent innervation I mean the whole muscular innervation involved in distance adjustments, be it of the eye or lens muscles. The term "convergent innervation" has been used for the lack of any adequate term covering the whole innervating act of binocular adjustment.

XVI. Explanation of the Third Dimensional Movements.

These movements are extremely complicated, probably being due to the coöperation of a number of functioning factors: —

A. *Central processes.* It was evident that interpretation, or mental expectancy, had much to do with the movements. The importance of this factor probably varied with individuals.

B. *Peripheral processes.* Certain given factors were also at work determining the nature of the phenomenon, whose influence the central factor was never able to overcome. In fact the central process could hardly be supposed to function unless there were present some given data, some conditioning changes, to interpret. Among the nine criteria of depth, we have at least five present in this phenomenon: (1) Decrease of brightness, (2) indistinctness and vagueness of surface and contour, (3) decrease of size, (4) convergent changes, and (5) the binocular parallax. It is possible that a sixth factor — accommodatory changes — may be present.

The first three characterize the monocular image, and are all signs of increased distance: hence there is no reason for denying their functional efficiency in this case. However, they cannot

be the sole explanation, for they cannot account for the forward movements. Their backward effect must at times be overcome by other factors determining the forward direction. In binocular closure the image becomes larger with certain subjects. In this case the change of size would tend to produce forward movements.

(4) By *convergent changes*, I do not mean an actual movement of the eyes, but a change in the state of convergent innervation irrespective of the eye movements which may or may not occur. According to our previous hypothesis, such a factor will produce a distance change of the space reference, a backward or forward movement of the visual field. It is known that unitary binocular vision is a stimulus to the proper degree of convergent fixation; that unless the separation of the binocular images be too great, the eyes reflexly rotate to secure unitary vision. Hence if these conditions for maintaining a definite degree of convergent fixation be disturbed, the convergent tension will tend toward its normal state. If one fixates an object and suddenly intercepts the vision of the right eye by a piece of cardboard, the left eye's image of the object will be seen to move forward or backward. The left eye is stationary, but the right eye may be seen to rotate. If this rotation be divergent the image will move backward, while if it be convergent a forward image movement will result. With most people, it is asserted, the rotation is divergent because the external recti are stronger than the internal, and hence the normal position of the eyes approximates a condition of parallelism. Thus backward image movements generally result from this test. However, forward movements occur with those subjects whose internal recti are the stronger, or whose normal position of the eyes is a relatively convergent one. It is to be noted that the left eye is stationary in this experiment, yet its images move backward or forward, *i. e.*, the space reference changes its distance relationship to the head. This explanation of the phenomenon is given by James,[1] but he makes this

[1] James: *op. cit.* ii, p. 92.

movement of the left eye's images, or the space reference, a function of the feeling of rotation in the right eye. According to our conception, it would result from the changed conditions of convergent innervation, irrespective of the fact as to which eye happened to rotate. Additional proof of an altered state of convergence in this test is furnished by the fact that the images of the fixated object are found doubled when the cardboard is removed, but are immediately recombined by a reflex movement.

We have exactly the same conditions in the pressure and closure tests. The images are doubled, and with closure the stimulation in one eye is gradually intercepted. Unitary vision is destroyed and an opportunity is allowed for a return toward a more normal degree of convergent tension. Again this convergent factor applies to changes in innervation of both the ocular and lenticular muscles.

However, this factor would be operative only under binocular conditions. In the test with the cardboard, it was the image of the left eye which moved. Consequently with closure of the right eye the left field ought to move if the principle is operative, but the movement we are describing is a movement of the right eye's image in relation to the left field. This factor must be equally operative on both fields, while we are concerned with their difference of movement. Evidently this difference of movement could not be explained by this principle. Furthermore, if the closure of the right eye be executed while the vision of the left eye is intercepted by closure or other means, the condition of unitary vision will have been destroyed and the convergent factor will have already produced its effects before the winking begins. Consequently the factor has no effect under monocular conditions; it is only effective for binocular closure.

The directional effects of this convergent change vary for individuals. It might produce forward movements for one subject and backward movements for others. I am able to state the conditions for only four subjects. The external recti of subjects

2 and 4 are the stronger, and the eyes tend toward a condition of parallelism. Hence backward movements would result. Moreover, the strength of this tendency will decrease in proportion to the distance of the object fixated. The opposite conditions obtain for subjects 1 and 6. The normal condition of the eyes is one of convergence. Hence not only the extent of these movements, but also their direction will vary according to the state of convergence. For instance, if the fixated object were situated near the subject so that the eyes were converged more than in their normal condition, a backward movement should result, while the opposite result should occur for fixation positions beyond the normal position of the eyes. As a matter of fact the cardboard test on subject 1 gives pronounced backward movements for near distances, forward movements for extreme divergent positions, while the results are slight and ambiguous for the distance of the screen (290 cm.). Here the movement is small and its direction seems to be a matter of interpretation.

These four factors are insufficient to account for the whole of the phenomenon. A single illustration will suffice. Binocular winking at a near object situated in the median plane produces forward movements for subject 1. All the factors so far described would have a backward effect under these conditions. Hence some factor must be present not only to explain the forward movement, but also to neutralize the backward tendencies.

(5) *Binocular parallax.* With pressure or closure the eyes are forced to move in the socket and double images result. The stimulation from the fixated object now strikes the eyes as it would provided the object were situated either beyond or inside the point of fixation. If the images are doubled homonymously the object is perceived as if it were situated beyond the point of fixation; if they are doubled heteronymously the object is perceived as if it were located nearer than the point of fixation. Since the point of fixation, or the space reference, undergoes no distance change concomitantly with these enforced eye move-

ments, this gradual doubling of the images is the same effect as would be produced by an actual movement of the object out of the plane of fixation. The case is exactly comparable to the lateral illusions. A retinal shift identical to that of an actual third dimensional movement occurs with no corresponding correctional change of the space reference. Hence a third dimensional movement results. At least the conditions are present for a third dimensional interpretation.

It was once held that doubled images were always located in the plane of the point of fixation. If this were true, doubled images could not mediate a distance feeling according to our conception. The later and more prevalent view [1] maintains that doubled images are located somewhere between the point of fixation and the plane of the object. Hence homonymous images appear behind, and heteronymous images in front of the point of fixation.

This factor will operate for both monocular and binocular conditions — whenever there is any horizontal doubling of the images. Its strength will be proportional to the amount of doubling, hence the binocular effects will generally be the greater. Its directional results will be extremely varied. Homonymous doubling will produce backward movements and heteronymous doubling forward movements. Now the character and the degree of the doubling will vary among subjects under similar conditions of convergence and fixation position. Furthermore, it will vary for the same subject according to either the distance of the fixated object or the position of fixation. For instance, for any position on the screen between the zero points, binocular closure with subject 1 produces homonymous doubling — a backward movement. If the fixated object be brought near the eyes, a heteronymous doubling — forward movement — will result. In fact this is the only factor which can explain this forward movement for subject 1.

[1] Titchener: Experimental Psychology [Qualitative], Instructor's Manual, p. 254; Le Conte, *ibid.* p. 151.

(6) Accommodatory changes have been invoked to explain the changes in size, brightness, and distinctness of the images. These resulting image changes are criteria of depth. Thus accommodation is an indirect factor. Furthermore, changes in lenticular innervation may occur, but these possible changes have been embraced under (4) the convergent factor. Now the extraneous force may cause an accommodatory movement of the lens directly, irrespective of any muscular contractions, and the afferent feeling connected with this enforced movement may be an additional factor. However this assumption is rejected for the following reasons: (*a*) such a view is contradictory of our theory that efferent and not afferent processes control the space reference, (*b*) there are no positive grounds for such an assumption. Nothing definite is known as to the character of the assumed changes, and hence no factual correlation between them and the image movements can be established, (*c*) the assumption is not necessary to an adequate explanation of the third dimensional phenomenon.

No other functioning factors were found, and no single process is adequate to a complete explanation. Hence the conclusion is drawn that the phenomenon is a result of the coöperative influences of the various processes, one central and five peripheral factors. The extent and direction of any particular movement is the resultant of several factors acting in conjunction or opposition as the case may be. The number of the functioning factors, their strength and directional significance in any particular situation vary according to several circumstances, (*a*) the subject, (*b*) the fixation position, (*c*) the distance of the object, and (*d*) the conditions of the stimulation. Hence the wide variety and complexity of results is possible.

This conception will explain all the general features of the phenomenon which we have noted: the principles 4 and 5 will explain the facts (1) that the extent and direction of the movement vary among individuals in similar circumstances, (2) the marked influence of binocular conditions, and (3) that the

direction and extent of the movement vary according to the degree of convergence. The fifth principle accounts for the fact that the presence and extent of the movement vary for different fixation positions on the screen; it also accounts for the forward movement exhibited by subject 1 for near convergence. The influence of the interpretative factor is accounted for by central conditions. The first three principles explain the backward movements for monocular closure at the zero points. It is not meant that these are the only functioning factors in the above conditions, but that they are the significant ones in those particular circumstances.

XVII. The Space Significance of Ocular Innervation.

The conception of the function of ocular innervation previously outlined has a bearing not only upon visual illusions of motion, but also upon all detailed problems concerning the perception of distance, direction, and motion, and upon a general theory of space. Its significance in a space theory merits some attention.

One point in this conception must be carefully borne in mind, *viz.*, that the innervating impulse does not possess any independent function in space perception, free from the coöperating influences of afferent conscious processes. The efferent process has no corresponding sensory content of its own, but is supposed to act upon and to determine the space significance of the afferent contents. Without visual content, the motor factor could possess no spatial function. The efferent process is thus a fundamental, but a coöperating factor in space perception. The afferent conscious processes at least furnish the necessary stuff or material, without which the innervating impulse cannot operate as a spatially significant factor.

From this standpoint, the experimental procedure of attempting to evaluate the functional importance of "eye movement" in the various problems of visual space is radically wrong in its presuppositions. This method is that of isolation; it attempts

to estimate the influence of any factor (a) in securing a certain result, by eliminating or minimizing all other possible functioning factors. If the process (a) does not mediate the given result under these conditions, the conclusion is drawn that the process in question does not possess the supposed function. This procedure assumes that any factor can possess a function only independently, totally free from the coöperating influences of other factors. As an illustration of the experiments which have so minimized the functional importance of "eye movements" in visual space, we may cite the current test on the perception of motion. The object used is a small light of so weak intensity of illumination that no other objects in the visual field can be perceived. Under these conditions, movements appear when none are present (autokinetic sensations), and real motions are not perceived or are radically misjudged as to direction, extent, and rapidity. The factor of "eye movement" is isolated by suppressing as much as possible all visual data, and since under these conditions judgments are extremely unreliable, the conclusion is drawn that "eye movement" has little, if anything, to do in the perception of motion. This assumes that eye movements have a function only as they operate independently of other data.

Such experiments have not only radically minimized the importance of eye movements in space theories, but have left the question in a thoroughly disorganized and chaotic condition. But little unanimity of opinion is possible among writers, and even the same writer is not apt to ascribe to this factor a consistent and uniform importance throughout all departments of visual space. Dodge [1] has recently questioned whether eye movements have any function in the perception of motion, though it is doubtful if he would take the same position in regard to the influence of eye movements in the perception of distance. James [2] gives little importance to eye movements in the percep-

[1] The Participation of Eye Movements in the Visual Perception of Motion, Psych. Rev. xi, pp. 1–14.

[2] James: *ibid.* ii, pp. 91–93, 197–202.

tion of motion, yet the *feelings* of convergence and accommodation are significant factors in the perception of depth. In fact this seems to be the general tendency, to minimize the influence of this factor in visual motion, and still to ascribe to it a relatively large importance in the consciousness of static differences in distance or directional relationships. This, to the writer, is a rather anomalous position, for the movement consciousness is but the immediate awareness of change within a system of space experiences. Change is an ultimate and primal characteristic of consciousness; it represents the fact of the "stream" or "flow" of consciousness. Discrimination, the sense of differences, or the *consciousness* of change—of the flow —is also a primary and ultimate characteristic; for without it there could be no contents, no "stream" or "flow." These discriminated differences are many and varied, permeating all departments of conscious experiences; they may obtain between contents, within temporal or spatial experiences, or within a system of logical relationships; they may be simultaneous or successive, or may be static and disparate on the one hand, and changing, gradual, continuous, or flowing on the other. This sense of change, of the flowing type of experience, within a spatial system is the movement consciousness. This conception makes the movement consciousness immediate, a primary and ultimate characteristic of space experiences. However, it does not imply a "sensation" of movement in the content meaning of that term. Such a sensation of movement is no more necessary than a similar "sensation" of difference between the contents red and blue. The term "content" to have any meaning presupposes discrimination, or the consciousness of difference. However, it is well known from experimental tests that in temporal or spatial experiences our sensitivity to these flowing differences is more acute than to those of a static, or disparate character, for a consciousness of these latter implies to some extent their overt definition or location within the system; our sense of change is more keen than our ability to tell what or how

much the change is. Hence to assign to eye movements a greater importance in the discrimination of differences in distance and directional positions than in the mere sense of change within these relationships, is to controvert a well-established truth.

I do not deny *in toto* the relevancy of the method of elimination; it has its uses, but the conclusion must take strict account of the conditions of the test. When possible, this method of actual elimination should be supplemented by a method of logical elimination, a comparative study of many different cases in which all but the factor in question are variables. However, we do maintain that these tests are not relevant to our theory; that while eye movements may not have an independent function because of their afferent conscious processes, yet still they may be of fundamental importance because of the innervating process functioning in a spatial manner only in conjunction with conscious data. The tests do support our contention against the afferent theory. Furthermore, such a conception offers the possibility of ascribing to the fact of eye movement not only a uniform and consistent function in space, but also an importance commensurate with that which logic and common sense would seem to demand.

As a positive illustration of the method in which innervation and conscious data may be conceived to coöperate functionally in space judgments, we may refer again to the Hering convergence phenomenon. Two objects are located in the line of sight of the right eye. With the left eye closed, the convergence is changed from one object to the other. The space reference, or the two objects and in fact the whole monocular field, moves to the right and to the left. The movement is not strikingly apparent unless the attention is directed to its perception, and unless the convergent motion is relatively rapid. Moreover, under these conditions its extent is quite small. If the left eye be now opened, but its vision of all objects in the right monocular field be intercepted by a small screen, a repetition of the test will give much more pronounced results; the movement is

more striking in appearance, and is at least three times as great in length. The effect is heightened still more by a removal of the screen. That is, the presence of extra visual data has rendered this shift of space reference more apparent as to its existence and magnitude; they do not, however, cause the two objects to actually move more than in the first case. This may be seen by quickly opening the left eye after the convergent act. The objects do not now undergo any additional movement because of the extra visual data; they remain entirely stationary, but their movement which formerly appeared but four inches in length is now judged to have a magnitude of 14 to 16 inches. The actual shift of the space reference is the same in the two cases, being conditioned by the amount of convergence; but the meaning, the interpretation, or our consciousness, of this shift as to its occurrence and amount is mediated by the visual data. In other words, the innervating impulse in controlling the retinal space reference constitutes a system of given fixed spatial conditions which are imposed upon and are in turn interpreted by the resulting sensory contents.

This illustrates the general conception of the function of the innervation factor in a space theory. The "retinal space reference" means a varied and complex system of fixed and given conditions determining the distance and directional relations which any possible visual experience must bear to tactual-motor experiences. These conditions may be regarded as *a priori* forms as it were, for they are imposed upon the visual experiences; they determine the space significance of the retinal processes. The same retinal conscious process must possess a different space value or characteristic, *i. e.*, must stand in a different space relation to the body, for every degree of effective innervation. These conditioning factors existing between visual and organic experiences are mutual and reciprocal in their implications. They not only condition the possible relations of a visual process to bodily space experiences, but *vice versa*. For the same purpose, and for the same retinal process, a different organic

adjustment is demanded for every degree of effective innervation. These conditions are imposed upon, and determine the nature of organic adjustments to visual experiences. On the other hand, this system of space *conditions* is empirically worked out into a system of space *relations* through the conscious processes concerned in vision and movement. What these conditions mean, their interpretation, their value and significance, is derived from the various conscious data. Thus the innervation factor forms a bridge, a point of contact between these two kinds of space experiences through which they become mutually organized and coördinated, through which they become mutually interpreted and transmuted in significance. Not only this, but by relating the two kinds of space, by furnishing each a point of reference, a common denominator, it makes possible one means at least of mutually relating or coördinating the various parts of each in a more synthesized system of space values. Without such a fixed given mediating system of determining conditions, the construction of a system of unvarying, constant and stable functional relationships between the two experiences would be impossible.

The factor of innervation thus represents certain given nativistic basic conditions whose elaboration into space meanings — space relations — represents the coöperation of sensory data — an empirical factor. By terming innervation a nativistic factor I do not mean to affirm or deny that it is the only nativistic factor. Moreover, it is not claimed that all sensory data are empirical in their space significance. The statement stands for the known fact that there are many conscious cues and processes of manipulation by which our visual and tactual-motor space experiences are each elaborated and mutually coördinated into some organic functional union. Moreover, we do not necessarily affirm that the innervation factor is ultimately, or phylogenetically, nativistic; we merely assert that such is the fact in adult life and apparently throughout ontogeny.

APPENDIX

APPENDIX—GENERAL RÉSUMÉ.

I. Illusory movements occur with closure as with finger pressure. These movements have both a lateral and a third dimensional component. Their direction and extent vary with the position of the eye in the head. With some subjects there are positions of no movement (zero points). The purpose of the paper is to study their determining conditions in relation to the concomitant physiological changes.

II. Apparatus and Method. A screen with a system of horizontal and vertical lines; small electric light as a fixation object; head fixed in an adjustable mouth-bit head-rest. The direction and extent of the movements are determined in reference to the system of lines for any given position of the eyes in the head.

III. Lateral Displacements due to Closure. Zero points were possessed by three out of six subjects. There is but one point for each eye. The two points for each subject are the same distance below the point of fixation of the primary position, but the distance varies for subjects; this distance is an angular constant for all degrees of convergence. The points are equidistant from the median plane; this distance varies among individuals, and is a linear constant for all degrees of convergence. The point of fixation of the primary position is not always in the median plane.

Where zero points are present, the image movement for any fixation position is directed away from the zero point toward the periphery of the field of regard; the length of any movement has a given relation to the distance of the fixation position from the zero point; this relation varies among individuals.

With subjects having no zero points, the direction and extent of the movements vary with the fixation position, but are similar for the two eyes. In some cases the presence of the movements depends upon the degree of convergence.

The occurrence, direction, and extent of the movements are functions of the position of the eye in the head, the degree of convergence, and the character of the closure. The movements refer to the entire visual field.

IV. With binocular closure each field moves relatively independently of the closure of the opposite eye.

V. A nasalward finger pressure generally produces the same effects as does closure. The direction and extent of these movements are functions of the position of the eye in the socket and the direction and intensity of the pressure.

VI. Suction produces the same results as closure.

VII. These lateral displacements occur for subject I. during extreme

peripheral rotations. The direction of the movement is toward the periphery of the field of regard, thus varying with the position of the eye in the head.

VIII. The movements are sometimes slightly curved, and the field may rotate about the line of sight.

IX. The movements with closure, pressure, and suction refer to the entire visual field, but their direction and extent vary for different parts of the field during the same displacement. The visual field is enlarged in that part of the field toward which the movement is directed.

X. The apparent size of the images decreases, their form changes irregularly, and they become less bright and much confused in surface and contour.

XI. Third dimensional components are present for most subjects in some conditions. The presence, direction, and extent of this component vary for subjects in similar conditions, according to the degree of convergence, the position of the eye in the socket and the character of the winking; they are also conditioned by an interpretative factor.

XII. The visual phenomena may be conditioned by (1) normal rotations of the eye, (2) refractive changes, or (3) rotary-displacement movements of the globe.

The image movements due to closure have been noted, but no explanation has been attempted. The movements due to pressure have been explained by normal eye rotations, but the rotation was assumed, and not proven. Authorities are sceptical of any displacement or refractive changes of the eyes, but nothing definite is known as to the changes occurring during closure or pressure.

Rotary-displacement movements of the eye, *i. e.*, a rotation about some center other than the normal center of rotation, are proven by several experiments: Ophthalmoscopic tests prove that the lateral image movements are conditioned by an appropriate shift of the retinal stimulation. The stimulation from an object affixed to the cornea is not shifted on the retina, and hence the image movements are not a result of refractive changes. The eyeball must move, and the character of the movement is determined from measurements of the corneal and retinal movements.

Refractive changes are evidenced by the presence of a slight movement of the object affixed to the cornea, movements of the iris, distortions of the form of the pupil, and changes in the images reflected from the lens. Nothing definite as to their character could be determined.

XIII. The visual phenomena due to the eye movements are the lateral image movements due to closure, pressure, suction, and normal rotations, and the sagittal rotations. The eye is not a perfect sphere, and is subjected to different tensions during rotation and convergence. Suction, pressure, and closure are disturbing mechanical forces. Hence the extent and direction of the image movements are conditioned by the position of the eye in the head, the degree of convergence, and the character of the disturbing force.

XIV. The visual phenomena due to refractive disturbances are the changes in the size, form, and brightness of the visual images and the unequal movements in different parts of the visual field.

XV. The point of fixation, negative after-images, entoptic phenomena, and the object affixed to the eyeball, *i. e.*, the images corresponding to a fixed place on the retina, do not move with pressure or closure, but do move with normal and superimposed rotations. The distance and directional location of a visual image corresponding to any point on the retina in relation to the position of the Cyclopean eye is called the "space reference of the retina." This space reference is made a function of ocular innervation. Illusions will occur whenever there is any discrepancy between the position of the eye and the space reference, or the state of innervation, *i. e.*, whenever the space reference changes when the eyes are still, or when the eyes move with no change of space reference. The illusions thus embraced are those due to (1) paralysis or paresis of the eye muscles, convergence, and prism distortions, (2) lid closure, finger pressure, suction, jars on the head, autokinetic sensations, extreme rotations. In the first class, innervation occurs with no proportional eye rotation, and in the second, the eye is moved by extraneous forces where innervation is not present.

The directional relation of the space reference to the head is a function of a synergic innervation (that tending to produce a parallel movement of the eyes) and the distance relation is a function of a convergent innervation (that involved in distance adjustments, whether it be to the lens or eye muscles).

The space reference is made a function of muscular innervation because (1) changes in space reference and changes in innervation are found together in all cases, (2) the space reference is not anatomically related to either eye, (3) it is not a function of the afferent conscious processes of either eye, (4) of afferent physiological processes, (5) of attention, or (6) of memory imagery; (7) there is no evidence in favor of the existence of "innervation feelings," nor (8) is there any *a priori* objection to making it a function of a purely physiological process.

XVI. No single principle of explanation can be found applicable to all cases of the third dimensional movements. The phenomenon is a result of a central factor and five peripheral factors working in conjunction. These peripheral criteria of depth are (1) decrease of brightness, (2) decrease of size, (3) confusion of surface and contour, (4) changes of convergent innervation and (5) the binocular parallax.

XVII. By controlling the space reference of the retinae, the ocular innervation furnishes a given and fixed set of conditions governing the possible relations between visual and tactual-motor space experiences. It thus makes possible a mutual definition and coördination of the one to the other. These *conditions* are empirically worked out and interpreted as *relations* through the afferent conscious processes.

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